1983

Design and Evaluation of a Solar Water Heating Package for a Solar Energy Intensifier-Thermal Energy Storage System

Charles Remund

DESIGN AND EVALUATION

OF A

SOLAR WATER HEATING PACKAGE

FOR A

SOLAR ENERGY INTENSIFIER-THERMAL ENERGY STORAGE SYSTEM

BY

CHARLES REMUND

A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Major in Agricultural
Engineering, South Dakota
State University
1983

DESIGHN AND EVALUATION

OF A

SOLAR WATER HEATING PACKAGE

FOR A

SOLAR ENERGY INTENSIFIER-THERMAL ENERGY STORAGE SYSTEM

This thesis is aproved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Advisor Date

Head of Major Department Date

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the entire Agricultural Engineering staff for their assistance and cooperation during this research. Appreciation is extended to Dr. W. Lee Tucker, Agricultural Experiment Station Statistician, for his help.

Special appreciation is extended to my advisor, Dr. Leslie L. Christianson, and to Mylo A. Hellickson, Agricultural Engineering Department Head, for their advice, guidance and assistance throughout the course of this study. Deepest gratitude is expressed to my parents, family and friends for their continual support and encouragement.

Thank you Mary for putting up with me through the the final weeks of this work.

CPR

TABLE OF CONTENTS

LIST OF TABLES

Table

page

LIST OF FIGURES

INTRODUCTION

Sources of farm energy, which include oil, natural gas and electricity, have more than doubled in cost over the past decade. This increasing cost of non-renewable energy plus the uncertainty of its availability initiated research efforts for alternate energy sources. One of these sources has been solar energy.

Farms with ample area for collectors, fuel reserves for backup or peak demands and a wide range of low to intermediate heat requirements provide excellent conditions for utilization of solar energy. However, the use of solar energy as an alternate energy source for agricultural applications has been restricted, largely by system costs. Since the initial investment in a solar system is the main cost of ownership, the more energy the system can provide over its lifetime the more economical it becomes. Multiple-use collectors offer a reasonable payback on investment and should be considered as a possible alternative energy source.

Research at South Dakota State University has led to the development of a multiple-use Solar Energy Intensifier-Thermal Energy Storage(SEI-TES) system for agricultural applications. Two applications for which the system has been tested and evaluated include grain drying and livestock ventilation air preheating. These applications utilize the system through the fall and winter, but additional use of the system through the spring and summer could improve the economics of the system by shortening its payback period. Water heating is considered as one potential additional use of the SEI-TES system. This led to research being conducted at South Dakota State University to:

1. Design a system to heat water using the SEI-TES system with minimal modification, while maintaining the performance of the SEI-TES system for grain drying and ventilation air preheating.

2. Test the SEI-TES water heating package under actual conditions.

3. Evaluate the performance of the SEI-TES water heating package and identify design parameters and operational variables that influence the performance of the system.

LITERATURE REVIEW

Energy Use in Agriculture

Agricultural, on-farm production consumes 2.4 percent of the annual energy use in the United States, Brewer(4). Of this amount, mobile uses, including tractors, field machinery and transportation account for 78 percent of farm energy consumption. The remaining 22 percent is used for stationary power and fuel needs for irrigation, lighting, appliances, home heating, crop drying, poultry brooding, etc. Excluding irrigation and electricity for lighting and appliances, stationary energy needs account for 10 percent of the total on-farm energy requirements, Heid and Trotter(9).

Sources of farm energy, which include oil, natural gas and electricity, have more than doubled in cost over the past decade, decreasing profits and causing some farmers to seek alternate sources of energy. One source of alternate energy being studied at South Dakota State University is that of solar energy.

The diffuse distribution of solar energy makes it best suited for relatively low temperature applications (less than 38 degrees centigrade), such as those found in agriculture. Solar collector systems that use liquid or air as heat transfer fluids are compatible with most commercial heating and drying systems used in agriculture, Brewer(4). The most promising areas are general low temperature heating, including grain and crop drying, livestock structure heating and greenhouse heating, agricultural processing and crop irrigation, Brewer(4). Most of these applications demand large quantities of energy. Grain drying and space heating, according to Brewer(4), offer the best opportunities for utilization of solar energy.

Grain drying and space heating, along with other farmstead uses for solar energy, are seasonal in nature(Figure 1). According to Hellickson et al. (11), crop and grain drying and farm building space heating can efficiently utilize low quality heat generated with a simple, inexpensive solar system. Spillman et al. (25) state that, since the initial investment in a solar system is the main cost of ownership, the more energy the system can provide over its lifetime the more economical it becomes. To achieve a reasonable payback on investment, the farmer should consider the use of a portable, multiple-use solar system, Heid and Trotter(9).

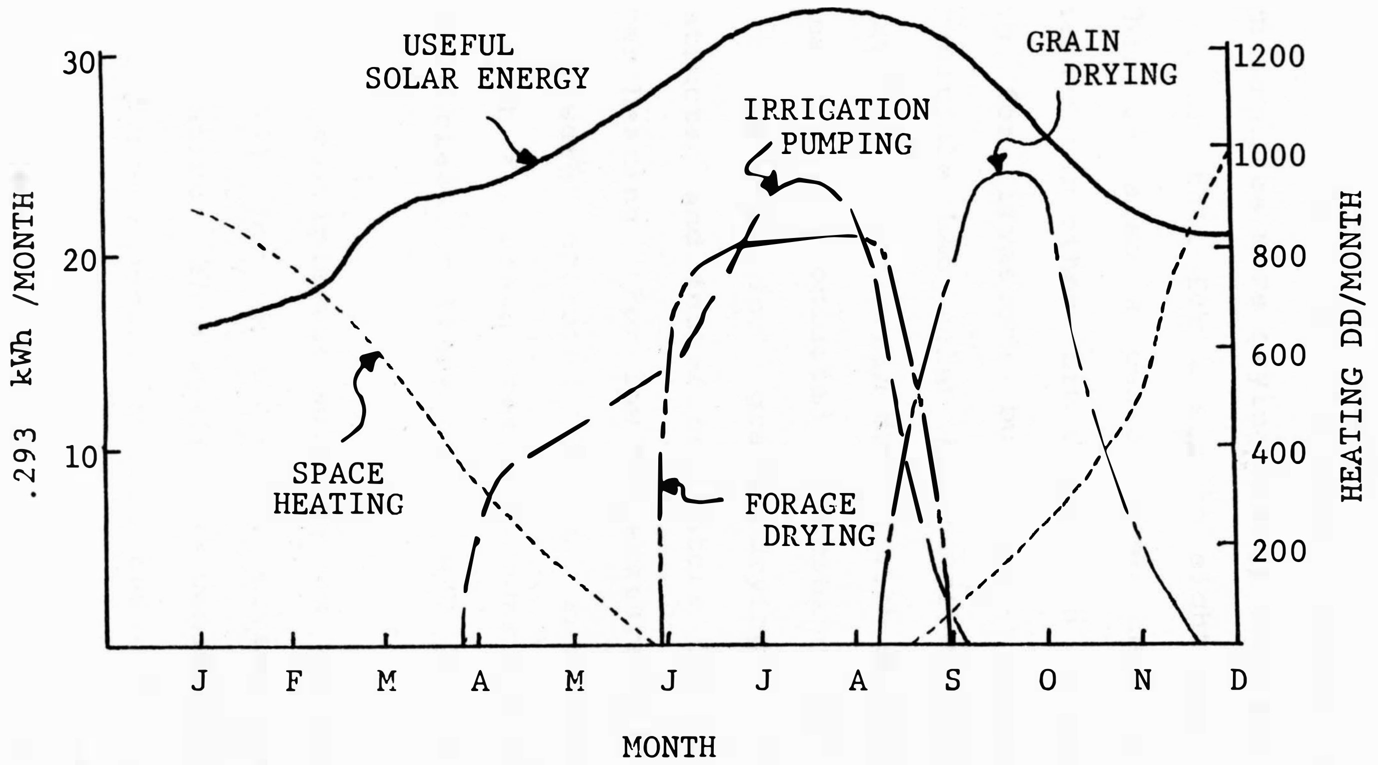

Figure 1: Load and Solar Schedule, Smith(24)

Grain Drying

Grain drying is a low temperature process normally limited to the fall of the year following harvest, Stout et al. (27). Corn requires more drying energy than most grains and is dried in the fall for a six to eight week period, Brewer(4). This is also a period when heat energy is normally not needed for other farm uses, such as ventilation air preheating for livestock buildings. According to Butler(5), a multiple use solar collector-storage system could be made available for grain drying with minimal cost.

Studies have been conducted concerning the use of multiple-use collectors for grain drying. Kline(14) designed, constructed and tested collectors for both grain drying and water heating. For low temperature grain drying the collectors were operated in a suspended plate configuration, with air drawn over and under the absorber. Noon hour efficiencies for these collectors ranged from 44 to 66 percent.

A stationary, multiple-use solar system was studied by Kocher et al. (15) for solar grain drying and swine farrowing house heating. This system was constructed on the south side of a farrowing-nursery unit and consisted of a concrete block wall with two glazing layers. Air was drawn through the system for ventilation air preheating in the winter and for grain drying in the fall. During the drying phase of operation the collector provided an average 2 degree centigrade temperature rise over an average ambient temperature of 2 degrees centigrade. An estimated savings of 0.43 cents per bushel of corn dried was noted.

A portable, multiple-use system was designed and tested by Hellickson et al. (11) for grain drying, livestock ventilation air preheating and water heating. This system consisted of a dual-sided triangular shaped collector with a reflector focusing on the north side of the collector. Grain drying studies with this system, when insolation averaged 26 percent below normal, resulted in an average daily temperature rise of 2.6 degrees centigrade, and an average collector efficiency of 37.9 percent.

Ventilation Air Preheating

Another use for the multiple-use solar collector is ventilation air preheating for livestock structures, Rode(22). Confinement livestock structures require the air be changed periodically to keep the humidity at an acceptable level and remove ammonia and other gasses, Butler(5). When the incoming ventilation air is colder than that required to maintain a set inside temperature, supplemental heat is usually added. Space heating requirements fluctuate widely and are generally limited to winter operations, although young livestock or poultry may require heat on a year-round basis. When supplemental heat is required, any heat that can be added from solar energy will reduce the heat requirement from some other energy source, Butler(5).

Studies using multiple-use collectors for livestock ventilation air preheating include a stationary system for grain drying and farrowing house heating, Kocher et al. (15) and a portable system for grain drying, ventilation air preheating and water heating, Hellickson et al. (11). The stationary collector was used to heat ventilation air and produced an average temperature rise of 9 degrees centigrade over an average ambient temperature of -8 degrees centigrade. The portable system utilized 0.21 cubic meters of rock storage per square meter of collector area to provide a thermal lag of approximately eight hours between maximum collector output temperature and maximum system output temperature. The portable system, over a 27 day test period, produced a 10 degree centigrade collector temperature rise and an 8.1 degree centigrade temperature rise for the air leaving the rock storage. The average collector efficiency was 31.2 percent and the average system efficiency was 24.5 percent, while insolation averaged 15 percent below normal.

Shop and Home Heating

Two additional winter uses of a multiple-use solar collector are shop and home heating. According to Rode(22), the basic grain drying collector could provide some shop heating capability if it were adapted to lower airflow rates. Recirculation of the air from inside the shop would lead to higher available temperatures from the collector. Residential heating is another possible use of the collector but, according to Rode(22), the system should be capable of providing temperatures in the range of 48 degrees centigrade to be effective. A recirculation system with multiple cover plates, modified air passage ways and adequate insulation would qualify as a residential solar heating system, Rode(22).

Hot Water Use in the Dairy Operation

An equivalent of 6.86 billion kilowatt-hours of energy is used each year in milking activities in the United States, Heid and Trotter(9). Table 1 provides a breakdown of this energy usage. A national study by the USDA in 1977 indicated that approximately 16 percent of the energy used on dairy farms was for water heating, Hellickson(10). This along with the rising cost of conventional energy sources has, according to Heid and Trotter(9), motivated a search for alternate sources for heating water.

TABLE 1

Energy Usage in a Dairy Unit

Water heating	35%
Milk cooling	26%
Milking	22%
Space Heating	9%
Lighting	7%

Commercial dairies require large amounts of energy to heat water for equipment cleaning and for stimulation and cleaning of udders. Brewer(4) states that about half of the energy needed for those tasks could be provided by low temperature alternative sources. Two low temperature alternatives receiving attention in the United States are solar energy systems and waste heat recovery systems. For dairies with fewer than 40 cows solar collectors may be more economical than heat exchangers, but for dairies with more than 40 cows most studies indicate that waste heat recovery systems save more energy and have a faster payback, Heid and Trotter(9).

In a commercial dairy, the use of hot water (75 degrees centigrade) and warm water (49 degrees centigrade) varies with its size, physical characteristics and mechanical arrangement, Brewer(4). For a given dairy, the required volume and time of usage of hot water is known. Hot water is necessary for proper cleaning and sanitation of all dairy equipment and warm water is used for udder washing and general cleanup, Stipanuk et al. (26). Aproximately 380 liters of hot water is used for cleaning short pipelines and 190 liters per wash is used to clean the bulk tank, Heid and Trotter(9). The use of warm water varies depending on whether automatic preparation stalls are used. With these stalls, approximately 7.5 liters per cow are used, while with manual preparation usage is reduced to about 1.9 liters per cow.

Equipment for the capture of solar energy is expensive and, according to Wiersma et al. (30), the capacity of the water heating components should be designed with regard to hot water use requirements. A solar heater designed to provide all the hot water required would be prohibitively expensive, Brewer(4). Thus Wiersma et al. (30) advises the use of solar energy to provide a major portion of the hot water requirements all of the time, or all of the hot water requirements a major portion of the time, and use conventional heating methods to assure the availability of hot water at all times. The capacity of the solar collector is increased if the water is heated only to the temperature at which it will be used because the efficiency of a collector is higher at lower circulating water temperatures.

The adaption and utilization of solar energy for use in dairies has been investigated by Hayden et al. (6), Hellickson(10), Stipanuk et al. (26), Wiersma et al. (30)

and others. A system studied by Wiersma et al. (30) at the Dairy Research Center, University of Arizona, provided about 20 percent of the required heating capacity for a 130 cow dairy using 4.09 square meters of collector area. This system heated water to approximately 65.5 degrees centigrade, requiring .0245 square meters of collector area per liter of hot water to do so. At the USDA Agricultural Research Center in Beltsville, Maryland, Hayden et al. (6) studied a 93 square meter flat-plate collector combined with 15,140 liters of water storage. The solar contribution of the system, used to heat the water and living space of a 200 cow herd, ranged from 16 percent in January to 59 percent in June, averaging 35 percent. Later studies of the same system documented an efficiency increase of 40 to 80 percent, with the entire collector array averaging nearly 55 percent. Hellickson(10) studied a water heating system consisting of six flat-plate collectors with a total area of 9.5 square meters at the Oregon State University Dairy Center. A 4700 liter fiberglass tank was utilized for hot water storage. Monthly efficiencies of the entire collector system, based on energy available and actual energy benefit, ranged from 18.1 percent in June to 47.8 percent in November.

Hot Water Use in Swine Farrowing and Nursery Houses

The commercial hog industry uses large amounts of low temperature energy for brooding baby pigs and for warming nursery and finishing units, Brewer(4). Of the 90 million pigs marketed each year, approximately 80 percent (about 72 million litters) receive supplemental heat during farrowing, NSF(19). On average, approximately 440 watts of supplemental heat is required per sow and litter, 24 hours a day for 35 days, resulting in the consumption of about 2.64 billion kilowatt-hours of energy per year. Common sources of supplemental heat are gas-fired heaters, electric radiant heaters, electric resistance heaters on or in the floor and hot water piping systems embedded in the floor.

Poor environmental conditions seriously hinder weight gain and increase death loss of baby pigs, Vaughn et al. (31). The highest proportion of piglet death loss due to chilling occurs during the first 72 hours after birth, Adams(1). During the first week of a piglet's life, it is desirable to provide heat in the creep area to maintain a temperature of at least 28 degrees centigrade, while ambient house temperature should be about 18 degrees centigrade, Vaughn et al. (31). According to Brewer(4), the ideal environmental temperature for newborn pigs is 32 degrees centigrade initially, decreasing to 21 degrees centigrade after 10 days.

Solar heat can be used to warm ventilation air, warm baby pigs by direct diffusion of warm air on litters and warm baby pigs by circulating heated air or water through the creep floor, NSF(19). A practical means of heating baby pigs is heating the concrete slab under them with electric heating cables or with hot water pipes embedded in the concrete. The latter method lends itself readily to the use of solar heated water, Brewer(4). Adequate hot water storage is a necessary part of a solar energy system to provide a continuous heat supply for young pigs during diurnal and extended periods of low solar availability.

Livestock farm solar demonstration projects are ongoing in nine states including nearly 90 farms. Half of these farms include solar heated swine facilities, Heid and Trotter(9). In Illinois, a system was designed to be used all year with both farrowing houses and nurseries. This system, now commercially available, included a 44.6 square meter, liquid-type, flat-plate collector. The estimated payback of this system was determined as less than five years. Auburn University studied a system in which water was heated and circulated through the floors of the creep and nursery area. McFate(17), at the university of Missouri, tested a system that transmitted solar-heated liquid to specially designed brooding pads in the creep area. Spot checks of efficiency, comparing solar heat available to heat gain across the collector, found efficiencies to range from 40 to 60 percent. System efficiency, which included two 3875 liter and two 1890 liter storage tanks, was somewhat lower, Meador et al. (18).

Domestic Hot Water Use

About 70 percent of all farm electricity consumption is used in the farm residence, Heid and Trotter(9). Water heating accounts for 12 percent of this amount. According to Hayden et al. (6), the use of a domestic water preheat device could reduce the cost of operating an electric water heater by approximately 35 percent, depending on water inlet temperature. It has been estimated that the use of solar energy for space and water heating in farm homes could save 29.3 billion kilowatt-hours of energy per year, primarily liquid petroleum gas(LPG), fuel oil and electricity, NFS(19).

Solar energy is, according to Studman(28), a tried, proven and renewable low temperature energy source particularly suited for domestic hot water systems. This is among the simplest and most efficient applications of solar energy, Heid and Trotter(9), while the residence is the most readily modified farm structure for alternate energy usage.

Solar Water Heating

Water has several advantages as a collecting and storage medium for use with a flat-plate collector. Water is low cost and has a high specific heat that, when compared to an equal volume of rock, allows three times as much thermal energy to be stored for the same storage temperature. Water can also be used more effectively than air when transferring heat over large distances. For many applications no additional heat exchange surface is needed to separate the air collecting medium and the liquid storage medium, Rode(22).

According to Kreith and Kreider(16), there are two types of solar water heating systems in common use, the natural-circulation (thermosyphon) system and the forced-circulation (pumped) system. Fluid motion in the thermosyphon system is caused by the tendency of low density fluids to rise above higher density fluids. This density difference is created in the solar collector by adding heat to the liquid, which increases the liquid's temperature and decreases its density. The forced circulation system utilizes a pump to circulate the liquid through the collector.

Solar Water Heating Collectors

Kreith and Kreider(16) discuss several methods for converting solar energy to heat energy at temperatures ranging from a few degrees above ambient to above 3000 degrees Kelvin. These range from air and liquid-cooled, non-concentrating, flat-plate type collectors to compound-curvature, continuously tracking types with concentration ratios up to 3000 or more. Low temperature units are generally flat-plate or evacuated-tube type collectors that operate below about 115 degrees centigrade, Brewer(4). Agricultural applications usually require temperatures less than 38 degrees centigrade, making flat-plate collectors readily adaptable, Brewer(4).

Most hot water collectors used today have tubes, attached to or built into the absorber surface, through which the liquid heat collecting medium flows. When water is to be heated with an air-cooled collector, an air-to-liquid heat exchanger is used. According to Rode(22), most air-cooled collectors are capable of satisfactorily heating water with the required heat exchanger.

Riley et al. (21) reported the use of an air-cooled solar collector utilizing an air-to-liquid heat exchanger in a domestic hot water system. Results indicated that this system performed less efficiently than two commercially manufactured water-heating systems (Model 60F Grumman "Bubble" collectors) on a solar contribution basis. The air-cooled collector contributed 0.0021 kilowatt-hours per square meter per day versus 0.0067 and 0.0084 kilowatt-hours per square meter per day for the commercial models. Two reasons cited for the lower solar contribution were that, in general, air-cooled collectors are less efficient than hydronic systems when used to heat water and, in this specific case, a 6.1 meter section of pipe running through an unheated space between the solar storage and auxiliary tanks was left uninsulated. Although less efficient than the commercial systems, the air-to-water system proved to be economically feasible, with a payback of 12.2 years for this particular system. Neither commercial system proved to be cost effective over a 20 year period.

Forced Circulation System

A forced circulation system is used when climatic, structural or architectural reasons prohibit the use of a natural circulation system, Kreith and Kreider(16). This system requires the use of a pump to circulate the water through the system. The addition of a pump allows for the storage tank to be located below the collector array, which is necessary when the collector is mounted on a roof or wall. The water flow rate can be varied when a pump is used to a rate which provides a desired output water temperature.

The collector can also be drained when a pump is used to prevent freezing in a cold climate. An increase in system cost and a decrease in system reliability are two undesirable factors encountered with the addition of a pump.

Thermosyphon System

The design of a thermosyphon collector system includes several factors related to the characteristics of natural circulation that must be considered. These include pipe size, storage tank elevation and storage tank size. Larger than normal pipe sizes and connections must be used to reduce friction losses in the water circulation loop. According to Kreith and Kreider(16), one pipe size larger than what normally would be used with a pumped system is satisfactory, but under no conditions should piping smaller than 1.1 centimeters be used.

The elevation of the storage tank above the outlet header of the collector is critical in two respects. First, the storage tank should be a least 0.3 meters higher than the collector outlet to prevent heat loss at night due to water flow reversal, Kreith and Kreider(16). Second, the elevation of the tank has a direct effect on the thermal head that causes the water to circulate through the system, Baughn et al. (3). Thermal head is the summation of the difference in the water density along the loop, vertically, times the vertical length of the loop.

Experimental work by Baughn et al. (3), illustrated in Figure 2, showed that the maximum flow rate decreased from 77.1 kilograms per hour to 38.6 kilograms per hour when the storage elevation was lowered from 0.6 meters above the collector outlet to 0.8 meters below. As the tank elevation was lowered, the system output temperature increased resulting in lower instantaneous efficiencies earlier in the day. However, at the lower tank elevations, the lower flow rate resulted in greater tank stratification which, according to Kreith and Kreider(16), is desirable to maintain flow rates and efficiencies as high as possible. At the higher tank elevation the higher flow rates caused the water to recycle through the collector in a shorter time. This resulted is less tank stratification, higher water temperatures entering the collector and high instantaneous efficiencies early in the day, but lower instantaneous efficiencies when recycling began. These lower instantaneous efficiencies resulted in the accumulated efficiency for the day being lowered. For the system studied, the accumulated efficiencies for the three tank elevations on similar days varied by only three percent at the end of each day, while earlier in the day variations in accumulated efficiency of up to 15 percent were noted.

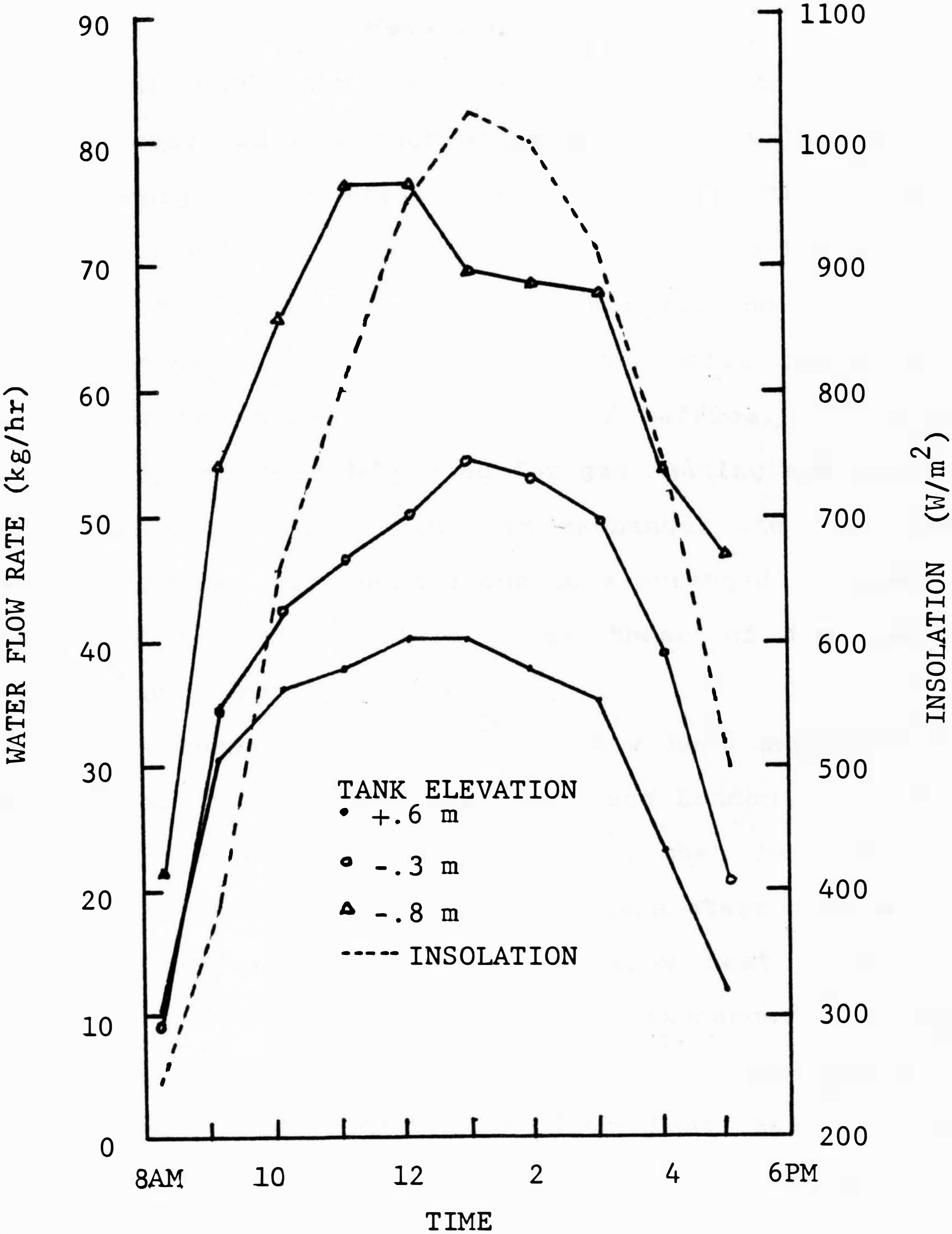

Figure 2: Results of Studies by Baughn et al. (3)

Heat Exchanger

A heat exchanger is a device in which two fluid streams, separated from each other by a solid wall, exchange thermal energy. One stream is heated while the other is cooled, Kreith and Kreider(16). Liquid-to-liquid heat exchangers are usually designed as a shell-and-tube bundle where one fluid flows through the tubes while the other is forced over the tubes by a series of baffles. Cross-flow heat exchangers are widely used for gas heating and cooling, Kreith and Kreider(16). In this exchanger the two fluids move in a number of separate channels arranged so that the streams of the first fluid cross those of the second, Henderson and Perry(12).

The performance of the cross-flow heat exchanger has been studied and documented by Kays and London(13). Shown in Figure 3 are effectiveness curves that resulted from these studies. Three dimensionless parameters are used to determine the performance of cross-flow heat exchangers. The first is the ratio of the exchanger's overall conductance (UA) to the heat capacity of the hot fluid (CaWa). The second is the ratio of the heat capacity of the cold fluid (CbWb) to that of the hot fluid (CaWa). The third is the exchanger effectiveness, which is the ratio of the temperature drop of the hot fluid (Ta1-Ta2) to the difference between the incoming hot and incoming cold fluid temperature (Ta1-Tb1).

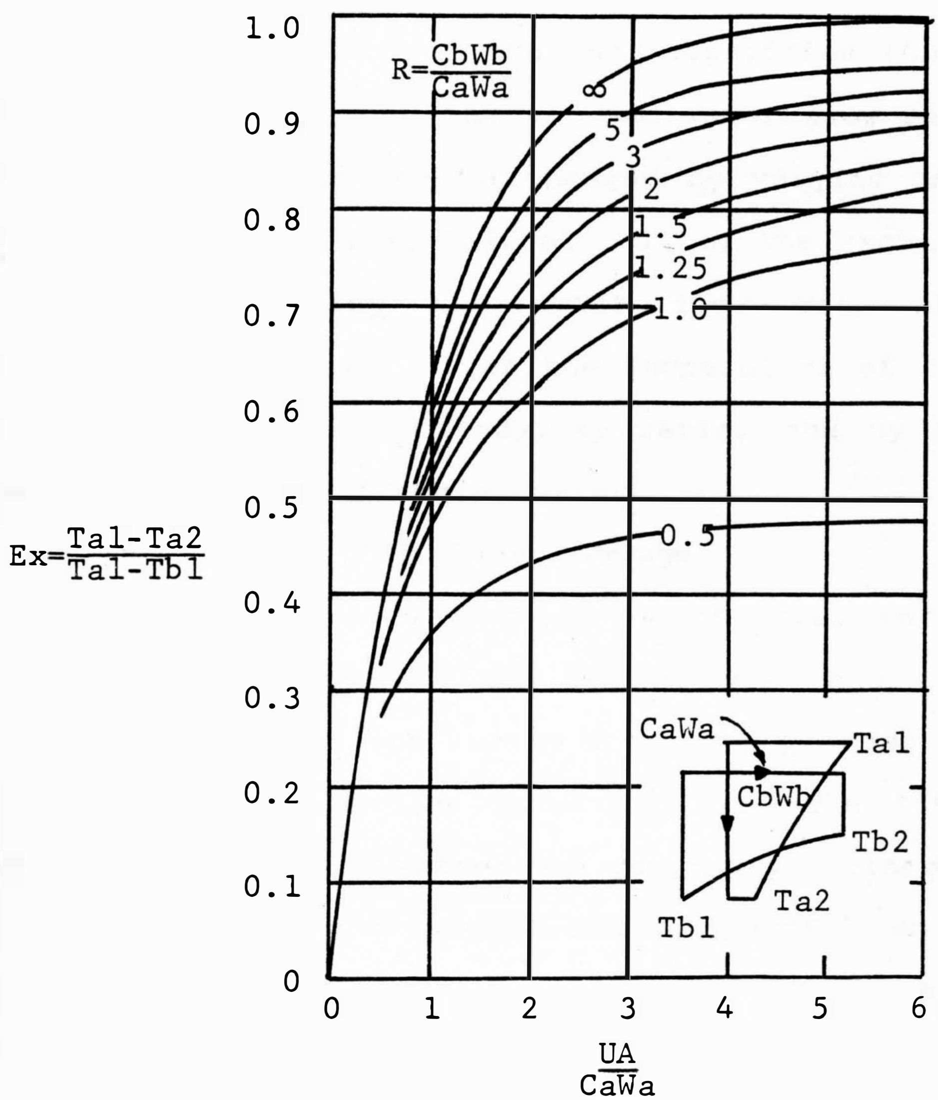

Figure 3: Cross-Flow Heat Exchanger Effectiveness Curves

For an air-to-water heat exchanger in which air is being cooled, the heat capacity of the hot air (CaWa) is determined directly from the air flow rate through the exchanger. Since the overall conductance (UA) is constant for a given exchanger, the dimensionless parameter UA/CaWa is influenced only by the airflow rate through the exchanger. The ratio of the heat capacities (CbWb/CaWa) is obtained directly from the air and water flow rates through the exchanger, and can be changed by varying one or both. The effectiveness (Ta1-Ta2/Ta1-Tb1) of the exchanger can be changed by varying the water flow rate through the exchanger, which influences the temperature of the outgoing air and also the heat capacity ratio, and by varying the temperature of the incoming water.

Energy Storage

Energy requirements of an agricultural enterprise can vary with time of day, day of the year and elapsed time since the start of the energy consuming process. Available solar energy varies in intensity with the time of day, season of the year, weather and geography. Since the supply of solar energy and the demand for useful energy rarely coincide exactly, solar energy must be stored for use at the time of need, Brewer(4). For the most efficient and trouble-free utilization of solar energy, the material type and quantity of storage must be compatible with other components of the system, the form and level of energy requirements and the availability of solar energy, Brewer(4).

Energy is stored in a material as either sensible or latent heat. In sensible heat storage, the storage medium increases in temperature whereas in latent heat storage the storage medium undergoes a phase change or chemical reaction, Kreith and Kreider(16). The most common means of storing solar energy is as sensible heat in a liquid or solid, Brewer(4). This type of storage is best suited for applications where the output temperature is not limited to a narrow range. Latent heat storage is better suited for applications with limited output temperature requirements.

The most common medium for storage of sensible heat with low and medium-temperature solar systems is water, Kreith and Kreider(16). Water is also the obvious choice if it is used as the heat transfer fluid in the collector or hot water is the desired end product, Brewer(4). Water has several other advantages as a storage medium including being inexpensive, readily available, non-toxic, easily transported and of high specific heat among others, Kreith and Krieder(16). Some disadvantages that must be accounted for include being subject to freezing, corrosion and leaking.

There are basically two modes of liquid heat storage, well-mixed and stratified. Well-mixed storage is at a relatively constant temperature throughout, while in stratified storage a temperature gradient exists in the medium.

Well-mixed storage usually occurs when liquid velocities at the tank entrance and exit are relatively high. The resulting turbulent flow causes a mixing action in the medium. Small storage volumes in comparison to the liquid flow rate will also result in well-mixed, or nearly constant temperature storage.

When the storage volume is large compared to the liquid flow rate, temperature stratification is possible. Stratification results when a less dense, warm liquid rises above a more dense, cool liquid, which falls to the bottom of the storage container, Brewer(4). Two major advantages are associated with storage stratification. First, the temperature of the liquid drawn from the bottom of the storage container is colder than that drawn out of well-mixed storage of equal size and energy content. Better collector efficiencies result because a colder fluid will pick up more energy in the collector. Second, more heat will be delivered to the point of use because liquid drawn from the top of stratified storage is at a higher temperature than well-mixed storage of equal size and energy content.

Evaluation of Thermosyphon Systems

Several researchers have investigated the performance of thermosyphon water heating systems. Baughn et al. (3) studied the effects of the elevation of a 113.6 liter storage tank on the performance of a 1.95 square meter flat-plate water heating collector. As mentioned in the Thermosyphon System section, higher tank elevation was found to cause higher water flow rates, smaller water temperature rises and instantaneous efficiency peaks to occur earlier in the day. For the tank size studied, the accummulated efficiencies were found to differ by only three percent at 5:00 p.m., and ranged from 50 to 54 percent. Baughn et al. (3) noted that, for other water use conditions, marginal solar insolation and different size storage tanks relative to the collector area, the effect of storage tank elevation may be more significant than results from his observations indicated.

The effects of elevation of the storage tank on the performance of a thermosyphon system were also studied by Ong(20). A 1.53 square meter collector was used with a 106 liter storage tank. Tests were conducted with the bottom outlet of the storage tank 0.84, 0.69, 0.53 and 0 meters above and 0.23 meters below the outlet of the collector. Maximum system efficiencies ranged from a high of 63 percent, on a day with the highest total radiation and the tank at the second highest elevation, to a low of 30 percent, on a day with 33 percent less radiation and the tank positioned at its lowest elevation. Generally, the lower tank elevations produced lower efficiencies. Conclusions were that by increasing the height of the tank the water mass flow rate was increased, resulting in lower collector temperatures and higher collector efficiencies. At higher water flow rates, the volume was recirculated through the collector more times resulting in more energy being collected and higher tank temperatures at the end of the day. Results of tests at the highest tank elevation seemed to indicate that there could be an optimal elevation between storage outlet and collector outlet, beyond which mean efficiency and tank temperatures may decrease, possibly due to increased pipe losses.

A system studied by Shitzer et al. (23) included two flat-plate collectors connected in parallel, with a total area of 3 square meters, connected to a 140 liter storage tank. Based on total insolation on the plane of the collector and total energy accumulated in the storage tank, the system operated with an overall thermal efficiency of 35.3 percent. Water flow rate in the system reached a maximum of 570 liters per hour at 13:00 h local time and declined into the late afternoon hours. Water temperature distribution inside the storage tank, under conditions of no water draw-off, was almost linear indicating good temperature stratification.

Baughn(2) studied the flow and temperature response of a flat-plate solar water heater with natural circulation to test the adequacy of an analytical model. Four collectors, with a total area of 4.36 square meters, were connected to a 310 liter storage tank which was elevated 0.34 meters above the collector. The water mass flow rate reached a maximum of approximately 151 kilograms per hour between 13:00 and 14:00 h and dropped off in the later afternoon hours. Instantaneous efficiency for the system reached a maximum of 66 percent at 11:00 h with an accumulated efficiency of 51 percent at the end of the testing day.

RESEARCH PROCEDURE: DESIGN AND TESTING

System Design

The South Dakota State University Solar Energy Intensifier-Thermal Energy Storage (SEI-TES) system is designed to be a low-cost, portable, multiple-use solar unit for agricultural applications. These applications include grain drying, livestock building heating and water heating. A 3.05 meter high, parabolic shaped, polished aluminum reflector concentrates solar radiation on the north side of a 0.8 meter high collector unit(Figure 4). The collector unit, triangular in cross-section to provide for internal rock storage, has low iron glass glazing on the north and south sides to receive reflected and direct solar radiation.

The system is designed as modular units to enhance its portability between various applications on the farmstead. The reflectors are designed as 3.05 by 3.05 meter sections mounted on wooden post and steel support structures spaced at 3 meters. The reflector frame is designed with solid 1.27 centimeter square steel rods welded in a parabolic truss-type arrangement. Round steel rods 1.27 centimeters in diameter are welded to the square rods, horizontal with ground level, to provide the support over which the reflective material is stretched. A 5.1 centimeter diameter, solid, round steel rod, located at the middle of the reflector frame, serves as pivot support for the frame.

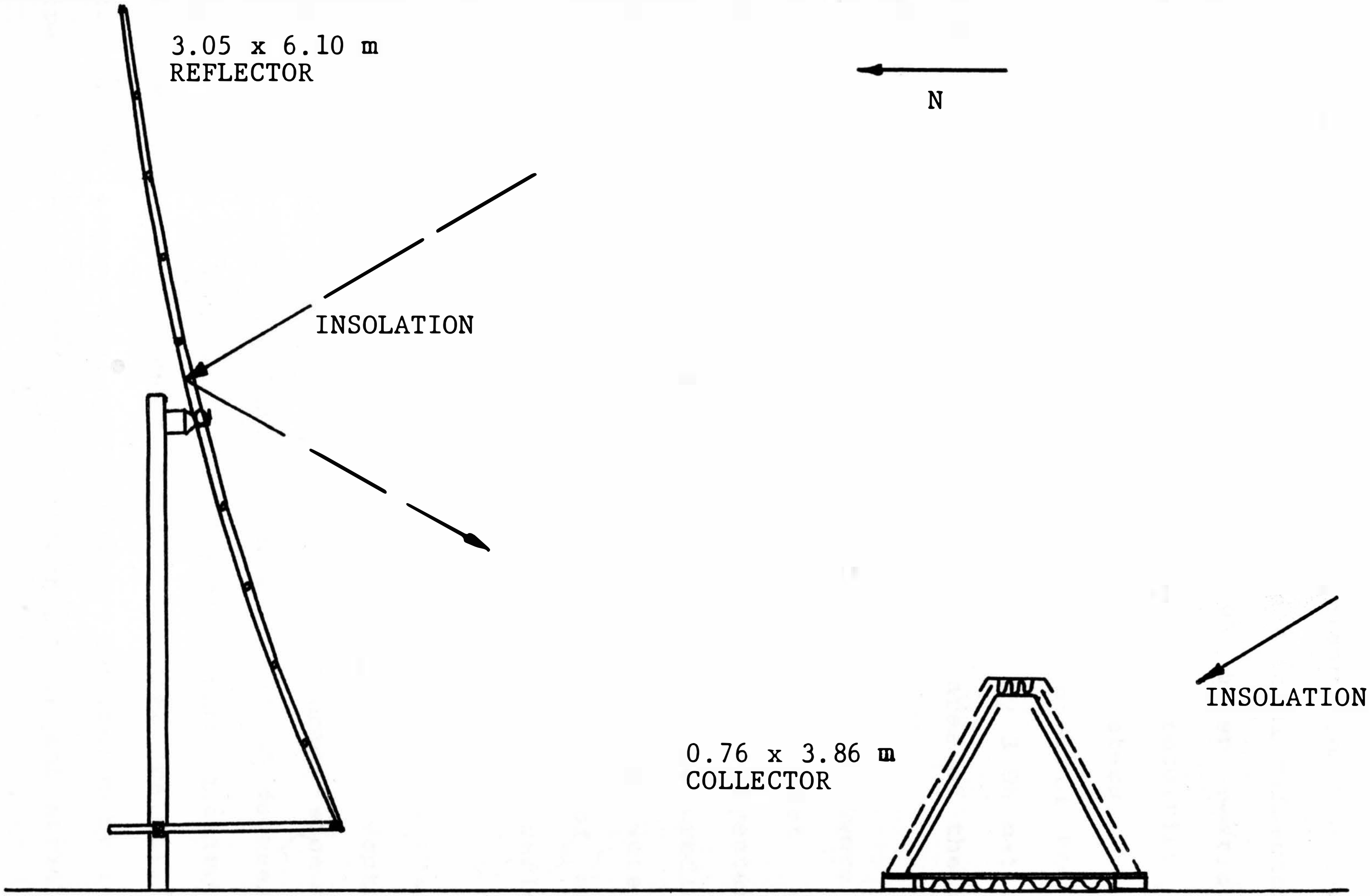

Figure 4: Profile View of Collector and Reflector

In both the 1981 and 1982 studies, two 3.05 by 3.05 meter reflectors were used to provide a total reflector area of 18.58 square meters. Two 1.93 meter sections of collector provided a 3.86 meter target, resulting in an effective area of 3.86 meters by 3.05 meters, or 11.58 square meters. When combined with the area of the south side of the collector unit, 0.86 meters by 3.86 meters, or 3.32 square meters, the total effective area of the system was 14.9 square meters.

In 1981, two types of reflective material were used. The first was a polished aluminum sheet called King-lux(reflectivity=.90) and the second, a polyester film with a vapor deposited, polished aluminum reflective material called YS-91(reflectivity=.85). The two were being compared with respect to durability as part of another study. In 1982 the King-lux was used as the reflective material.

The dual-sided, triangular in cross-section collector is designed to accept insolation directly on the south side and indirectly from the reflector on the north side. Both sides of the collector are at an angle of 60 degrees with horizontal, use 3.1 millimeter low-iron glass glazing, have a 0.8 millimeter sheet metal absorber painted with flat-black, laquer-base paint and are supported by an iron frame. Plywood behind the absorber plate, and attached to the frame, provides structural rigidity and forms the air channel behind the absorber(Figure 5).

The 1981 collector was designed and constructed as a continuous unit sized for its specific application. The 1982 system was redesigned and built in sections, 1.93 meters in length, each consisting of a separate north and south side unit. Each north and south side unit fit onto a base, designed for the particular application, and connected together at the top to form the triangular cross-section. The 1.93 meter sections fit together end-to-end to form basically the same collector unit as in 1981. The new design consisted of the same materials as before, but was more readily adaptable to different sized applications and more easily moved between each.

Different applications of the collector at different locations on the farmstead makes the use of a collector base unit, that is designed for the specific application, desirable. A flat base, constructed with 1.27 centimeter plywood and insulated with 5.08 centimeters of styrofoam is used for grain drying applications. A rectangular, trough-shaped base constructed of 1.27 centimeter plywood and insulated with 7.62 centimeter batt insulation is filled with 8 to 10 centimeter rocks and used for livestock building heating applications. The water heating application utilizes the same base as grain drying, but

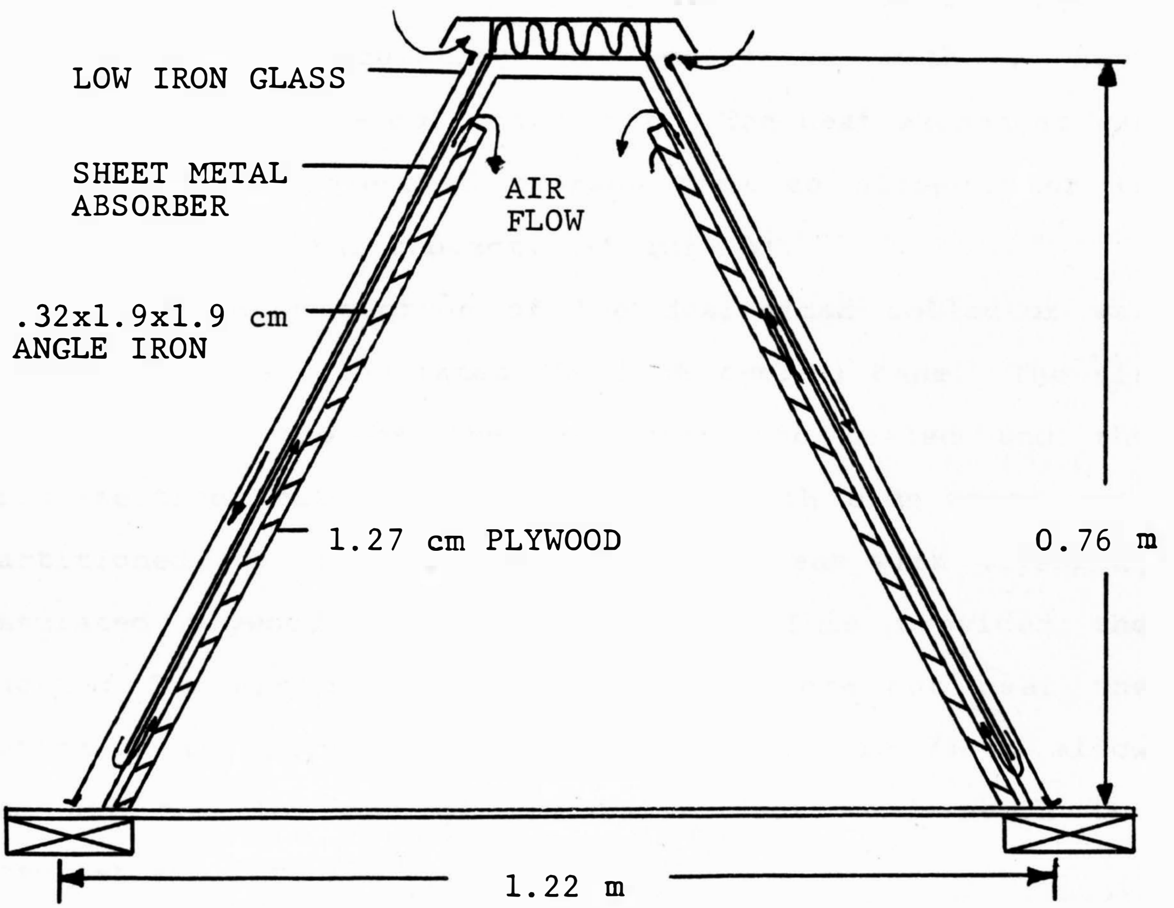

Figure 5: Cross-section of Collector Unit

ducting is added inside the collector, as described in the following sections, to provide for air recirculation.

1981 Water Heating Collector Design

The 1981 water heating system was designed as a single-pass, recirculating air collector with a heat exchanger inside the collector unit. The heat exchanger was connected to an elevated storage tank to allow water to circulate by natural convection(Figure 6).

A 3.9 meter section of the dual-sided collector was placed on a flat, insulated (R= 1.26 k-m2/W) base. The air inlet at the top of the collector was sealed and the cross-section, between the north and south side units, was partitioned into equal upper and lower areas with styrofoam insulated plywood (R= 1.26 k-m2/W). This provided the ducting for air recirculation. Holes were cut near the bottom of the plywood support structure(Figure 7) to allow the air to flow out of the lower duct, underneath the absorber and into the upper duct.

A 0.4 by 0.5 meter, finned-tube, air-to-water heat exchanger was placed inside the collector at one end. The exchanger was encased in plywood and air was drawn from the top duct down through the exchanger and exhausted into the lower duct. A 0.075 kilowatt forward curved fan, placed on the cold-air side of the exchanger, provided airflow in the system. It was calculated that a finned-tube heat exchanger

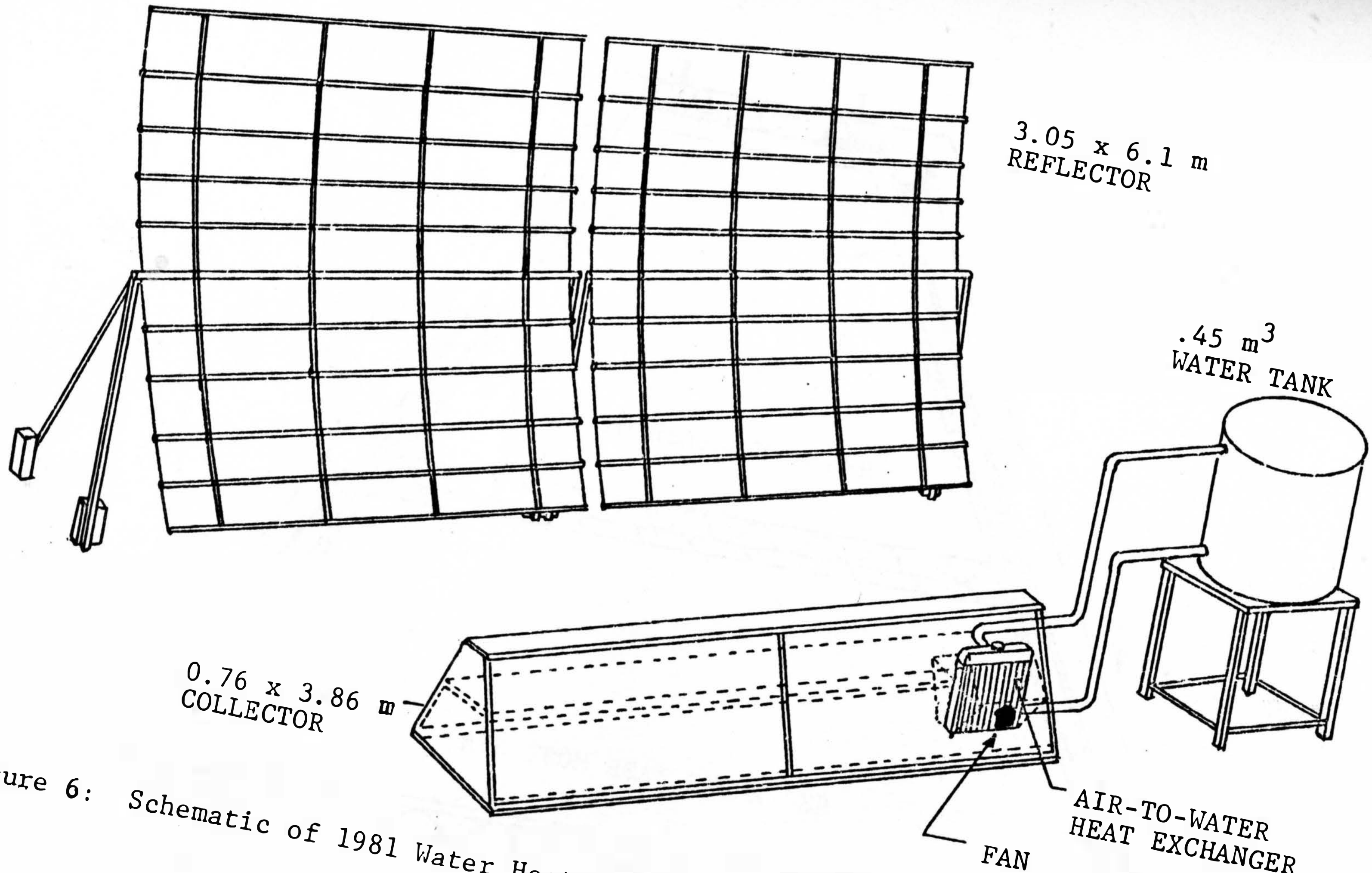

Figure 6: Schematic of 1981 Water Heating System

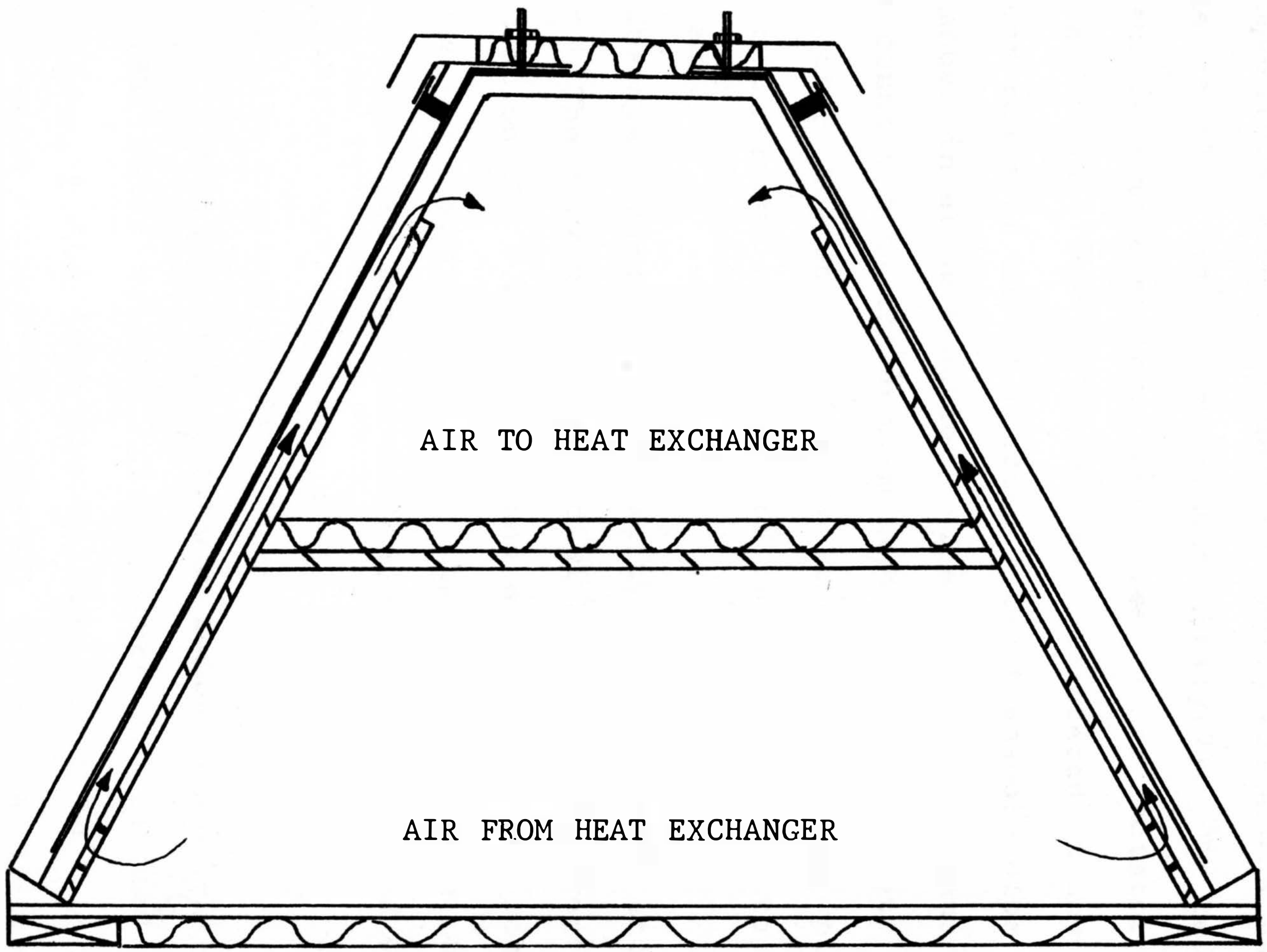

Figure 7: Airflow in 1981 System

with a face area of 0.194 square meters would be sufficient assuming a 53 degree centigrade air inlet temperature, a water temperature rise of 8 degrees centigrade and a water flow rate of 17.4 liters per minute, Healy(7). To reduce expense and determine system feasibility, a car radiator was selected and used. The exchanger was not altered in any way and regular radiator hose connected water transport pipes to the exchanger inlet and outlet. The cold water transport pipe was connected to the bottom heat exchanger inlet, and the hot water transport pipe to the top. These pipes extended out through the end of the collector and up to the storage tank.

A fiberglass tank with a capacity of 450 liters stored the water. The tank was insulated with 5.08 centimeters of batt insulation (R= 3.87 k-m2/W) and elevated so the bottom outlet was 0.3 meters above the top outlet of the heat exchanger. The tank and heat exchanger were connected with 2.54 centimeter wrought iron pipe insulated with 1.27 centimeter pipe insulation (R= 2.78 k-m/W).

1982 Water Heating Collector Design

The 1982 water heating system(Figure 8) utilized air recirculation, as the 1981 system did, but with the air making two passes over the absorber plate. A different ducting arrangement was required within the collector, but the same heat exchanger was used. The same storage tank was also used, but with a different type and arrangement of piping to the tank.

Two of the redesigned collector sections, with the same area as the 1981 system, were placed on a flat, insulated(R= 1.26 k-m2/W) base. The air inlet at the top of each collector section was sealed for recirculation. Dual-pass air recirculation was achieved by running a 15.2 centimeter wide, styrofoam insulated (R= 0.63 k-m2/W) duct down the center of the collector. The top of the duct was connected to the collector absorber plate on each side. Air flow was out of this duct, down over the absorber plate to the bottom where it turned up along the back of the absorber and finally exiting into the cross-section outside of the duct(Figure 9). Here the air was drawn to one end of the collector, through the exchanger and forced back into the center duct. A 0.124 kilowatt, axial-flow fan capable of operating at different speeds was used to circulate the air. The fan was located on the cold air side of the heat exchanger to minimize chances of overheating the fan motor.

The same heat exchanger was used in 1982 with one modification made on it. The outlet at the top and side of the exchanger was plugged and the radiator fill hole was utilized. A 5.08 centimeter diameter brass pipe was soldered into this hole to form a connection to the hot water transport pipe. This alteration was made to reduce

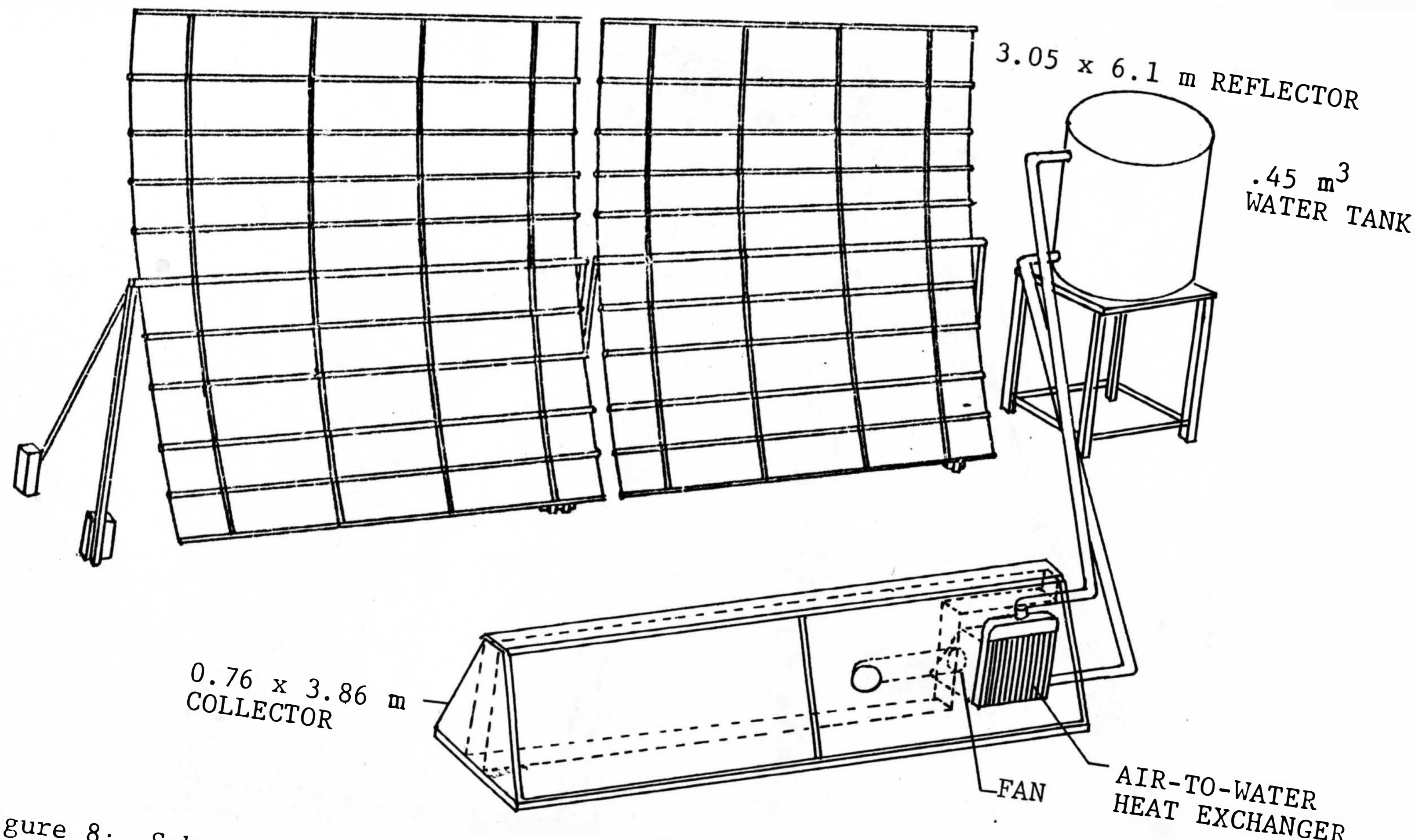

Figure 8: Schematic of 1982 Water Heating System

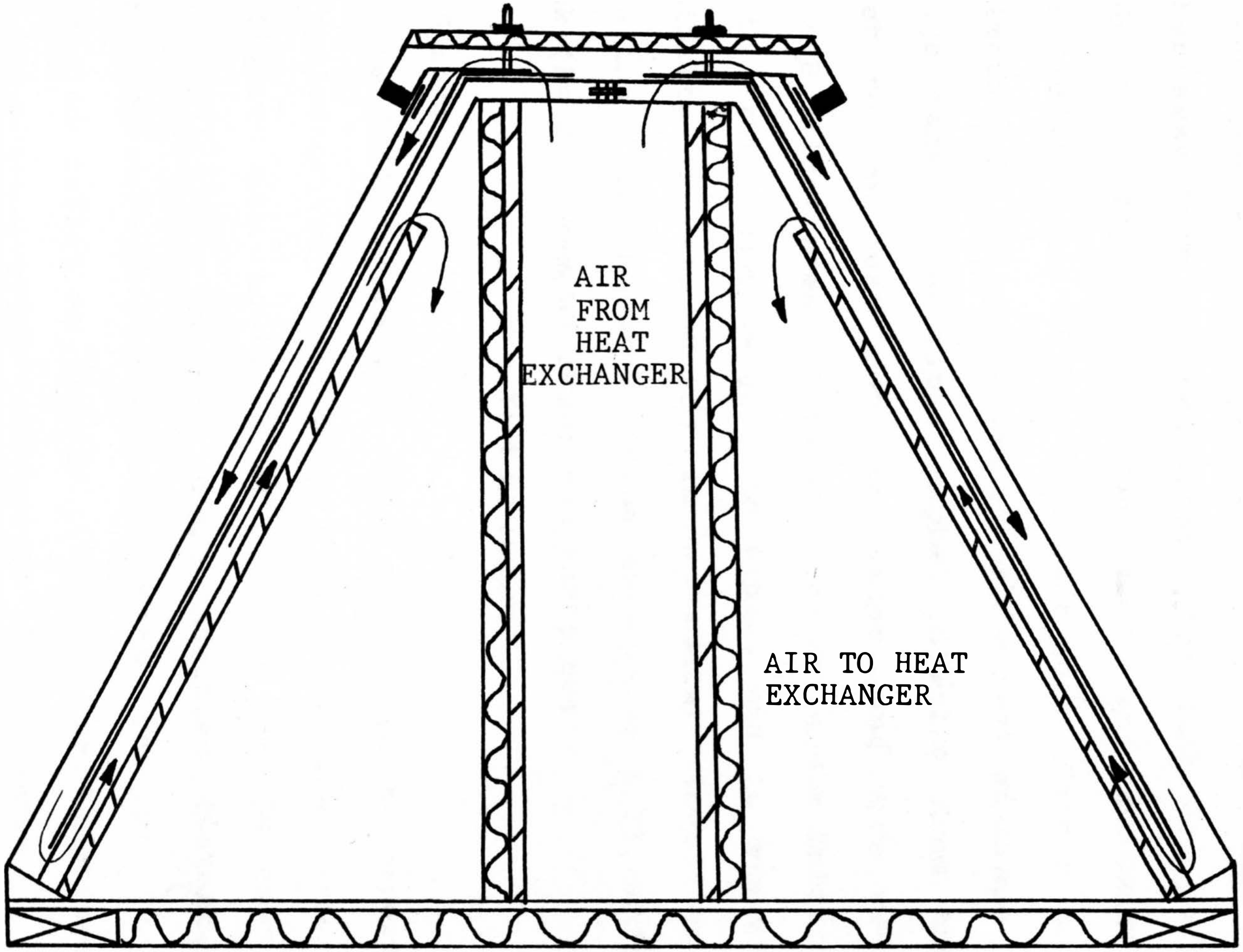

Figure 9: Airflow in 1982 System

the flow path length of the hot water in the heat exchanger once it passed through the heat transfer coils.

The same storage tank was used in 1982, but was set further away from the collector. The tank was positioned beside the reflector, 3 meters north and approximately 2 meters to the side of the collector end. Copper pipe, 1.9 centimeters in diameter, connected the heat exchanger to the storage tank. The pipes angled directly from the tank outlet to the heat exchanger inlet, and vice versa, as Figure 8 illustrates. This was done to reduce friction loss due to extra pipe length and elbows and to minimize the possibilty of trapped air in horizontal pipes, which can block the flow of water. Foam insulation 1.27 centimeters thick (R= 2.77 k-m/W) insulated the pipes.

Test Procedure

1981 System

The 1981 system was built and tested to determine if the collector, presently being used to dry grain and preheat ventilation air, could be effectively used to heat water. Major objectives of the study included evaluating the effectiveness of the thermosyphon concept, with an air-cooled collector and air-to-water heat exchanger, and evaluating the overall performance of the system.

Two parameters considered to be important in the system design were the air flow rate through the collector and heat exchanger, and the storage tank elevation. For this study the bottom of the tank was placed 0.3 meters above the exchanger outlet, as recommended by Kreith and Kreider(16), to prevent backflow during cloudy periods. A 0.075 kilowatt, forward-curved fan was selected to provide an air flow of 0.305 cubic meters per minute per square meter of collector, which required a fan output of 4.53 cubic meters per minute. The measured air flow rate in the system was 6.12 cubic meters per minute (446 kilograms per hour), which was slightly higher than desired at 0.41 cubic meters per minute per square meter of collector.

The collector was tested on relatively clear days between 9:00 and 15:00 h local standard time. The tank was filled with fresh water in the morning and the water transport pipes were checked for trapped air. The reflector was tilted downward to focus on the collector and the fan started.

Air and water temperatures were monitored throughout the day using copper-constantan thermocouples and a micro-processor, data aquisition system. A total of 44 thermocouples were used, of which 33 monitored air temperatures and 11 water temperatures.

Air temperatures were recorded at three cross-sections of the collector, at the middle and two feet from each end. Five thermocouples were placed at each section. One was placed at both the air inlet and outlet of the absorber plate on both the north and south sides, and the fifth between the two absorber outlets to record the temperature of the mixed air leaving the collector plates. The temperature of the air entering and leaving the heat exchanger was measured with 18 thermocouples, 9 spaced equally on each side. Ambient air temperature was measured with a thermocouple shaded from direct sunlight.

Five thermocouples were placed in the storage tank, one at each midpoint of five equal intervals between the tank inlet and outlet. A thermocouple was placed in both the tank inlet and outlet leading to the collector, and one was placed in both the water supply inlet and hot water outlet of the tank. The remaining two thermocouples were placed in the inlet and outlet of the heat exchanger.

A Hewlett-Packard model 9825 microcomputer along with a Hewlett-Packard model 3495A scanner and model 3455A digital voltmeter were used to obtain and record temperatures in the system. Temperatures were monitored and recorded every 30 minutes and stored on magnetic tape. An Eppley model 8-48 radiometer, controlled by the data aquisition system, monitored solar radiation for one minute at the end of each 30 minute interval.

Data were recorded from July 6, 1981 to August 8, 1981. The length of each test varied depending on any problems encountered on that given day. The first year's tests were conducted mainly as proof of concept, however, enough data were collected to evaluate the performance of the single-pass, thermosyphon system.

1982 System

The 1982 water heating system was built and tested to determine the effects of air flow path, air flow rate and storage elevation on system performance. Air flow was dual-pass, over the front and back of the absorber plate, to provide data that could be compared to the 1981 single-pass results. Air flow rate inside the collector affects the efficiency of the collector and the effectiveness of the heat exchanger. Tank elevation affects the thermal head, or the pressure in the water loop, that induces flow around the loop.

The 1982 system was tested using three air flow rates and three tank elevations. Due to lack of time needed to test all nine combinations, four combinations of air flow rate and tank elevation were used. Airflows of 7.02, 5.64 and 3.90 cubic meters per minute (504, 405 and 281 kilograms per hour), or 0.474, 0.378 and 0.264 cubic meters per minute per square meter of collector, respectively were used. Tank elevations used were 0.3, 0.6 and 0.9 meters, with the elevation being the vertical distance between the exchanger outlet and the storage outlet.

A total of 56 thermocouples were used to monitor system temperatures in 1982. Thirty-seven monitored air temperatures and the remaining 19 water temperatures. Thermocouples were placed at three cross-sections of the collector, the middle section and a section 0.6 meters from each end. Six thermocouples were placed at each section. The air temperatures entering and leaving the absorber plate and the air temperature where the air turned from front to back of the absorber were monitored in both the north and south sections. Nine thermocouples were equally spaced on both the hot and cold side of the heat exchanger. One thermocouple was placed in a shaded area to record ambient temperature. Nineteen thermocouples recorded water temperatures in the system with 14 equally spaced in the tank and one each in the exchanger inlet, exchanger outlet, tank inlet, tank outlet and water supply to the storage inlet.

The 1982 test procedure was similar to 1981 except data were recorded from 9:00 to 15:00 h local solar time. The same data aquisition system recorded system temperatures in 1982 as 1981, with more temperatures being monitored. The same radiometer was used in 1982, but radiation was monitored for 5 seconds every minute, instead of 1 minute every 30 minutes, and averaged at the end of the 30 minute interval. This was changed to minimize the effects of brief cloud coverings during the 30 minute interval, which helped prevent indications of complete clear or cloudy conditions during partly cloudy skies. This method provides a good measure of the average energy available over the 30 minute interval. Data were recorded for 33 days starting July 28, 1982 and ending September 10, 1982.

RESULTS AND DISCUSSION

Research was conducted in the summers of 1981 and 1982 to evaluate the performance of a solar water heating package for the SDSU SEI-TES system. In 1981 the system was designed and tested to determine the feasibility of the water heating package and limited data were obtained. The 1982 system was essentially the same as the 1981 system, except for a change in the airflow pattern. Data were collected for four combinations of three collector air flow rates and three tank elevations to evaluate their effects on system performance. Data from the 1981 and 1982 tests are tabulated in the Appendix.

The systems are analyzed on both a daily and hourly basis. The overall performance of both systems, including the different air flow and tank elevation combinations of the 1982 system, are evaluated on a daily basis.

An analysis of variance is used to determine the effects of collector air flow rate and water storage elevation on daily system efficiency for the 1982 system. An equation is given to predict the performance of the 1982 system based on collector air flow rate, insolation, and wind velocity. The 1981 and 1982 systems are compared to determine the effects of collector air flow pattern.

Prediction equations for daily energy collected for the different test combinations of the 1982 system are presented. The 1982 system is also analyzed on an hourly basis and prediction equations for hourly energy collected and temperature of the water leaving the collector are presented.

Several parameters and variables affect the overall performance of the thermosyphon water heating system. Design parameters considered to be important are the collector air flow pattern, collector air flow rate, size of heat exchanger, size and geometry of water piping system, elevation of the water storage tank and the size of the water storage tank. Parameters evaluated include collector air flow pattern, collector air flow rate and water storage elevation.

Climatic variables considered important include insolation, wind velocity, ambient air temperature and time of day. The average temperature of the water in the storage tank is considered an important system variable. Variables evaluated include insolation, wind velocity, ambient air temperature, time of day and water temperature in the storage tank.

The analyses of daily system efficiency include the effects of insolation, wind velocity, average ambient air temperature and initial water storage temperature for four combinations of air flow rate and storage elevation. The analyses of hourly system efficiency include the effects of insolation, time of day, ambient air temperature and temperature of the water entering the collector. The output water temperature analyses include the effects of insolation, average water storage temperature and incoming water temperature. The daily and hourly efficiencies are expressed in terms of energy collected in the prediction equation analyses.

Daily Energy Collected

Table 2 lists the average efficiency for each air flow rate and tank elevation from data collected in 1982, and the average efficiency for the 1981 data.

TABLE 2

Daily Efficiency

System	Average Efficiency(%)	Observations
1982 M=405,H=0.3 m	24.5	12
1982 M=281,H=0.3 m	20.0	3
1982 M=504,H=0.6 m	25.8	7
1982 M=504,H=0.9 m	26.5	6
1981 M=446,H=0.3 m	28.5	4

M= collector air mass flow rate, kg/hr
H= tank elevation, m

An analysis of variance was used to determine if the four combinations of air flow rate and tank elevation of the 1982 system produced results which were significantly different. For the given number of observations with four combinations, a minimum of 4.1 percent difference in daily efficiency is required for any combination to be significantly different from any other. The results indicated that, at an air flow rate of 281 kilograms per hour with the tank outlet 0.3 meters above the collector outlet, an average daily efficiency of 20.0 percent was significantly(.05) lower than the others.

Stepwise multiple linear regression was used with the 1982 data to predict system efficiency using collector air flow rate, insolation, daily average wind velocity, daily average ambient temperature and storage elevation as independent variables. Daily insolation, collector air flow rate and daily average wind velocity were the only variables having a significant(.01) effect. The equation is listed below with efficiency(Eff) in percent, collector air flow(Mair) in kilograms per hour, daily insolation(I) in kilowatt-hours and daily average wind velocity(Vw) in meters per second. For this equation the coefficient of determination was 0.776.

$$Eff = 20.69 + .0357Mair - .1475I - 1.013Vw$$

The sign of the coefficients for collector air flow and daily average wind velocity are as would be expected, with larger collector air flows increasing system efficiency and larger daily average wind velocities decreasing system efficiency. The sign of the coefficient for daily insolation is negative, which is not what what would be expected. There are at least two possibilities for this negative coefficient. First, the coefficients for each variable were based on its average value. When insolation was higher than the daily average, the heat losses from the system increase due to higher than average system temperatures. Second, the water inlet temperature was lower than ambient temperature during most of the day. At low insolation this will lead to efficiencies greater than 100 percent, because the system will pick up the largest amount of energy from the environment.

Daily average ambient temperature and storage elevation did not have a significant effect on the prediction equation. It is probable that there was not enough variation in ambient temperature over the 1982 test period, thus limiting its effect on the system efficiency. It is believed that storage elevation would have a significant effect on system efficiency if the storage volume were larger. As it was, at the higher storage elevation the water started recycling earlier in the day due to the higher water flow rate, increasing the temperature of the water entering the collector and decreasing the collector efficiency later in the day. With larger water storage, the water would not recycle as quickly and the efficiency of the collector would continue high later in the day.

The 1981 and 1982 systems were compared to determine if the two different air flow patterns, described in the Design section, resulted in different system efficiencies. Figure 10 is a graph of the average daily system efficiency of the 1981 and 1982 systems versus collector air flow. The 1982 data are graphed as a function of tank elevation, also, to isolate the effect of storage elevation. The 1981 system was tested at a storage elevation of 0.3 meters, as were two collector air flow rate and storage elevation combinations of the 1982 system.

To estimate the efficiency of the 1982 system for the collector air flow rate of the 1981 system, a line was drawn through the 1982 data which had a 0.3 m storage elevation. This line lies above the efficiencies of the higher storage elevations and air flow rates of the 1982 system, which suggests that the effect of storage elevation on system efficiency is non-linear over a wide range of collector air flow rates. Theoretically, the efficiency for a storage elevation of 0.3 meters and a collector air flow rate of 504 kilograms per hour should fall below those of the higher

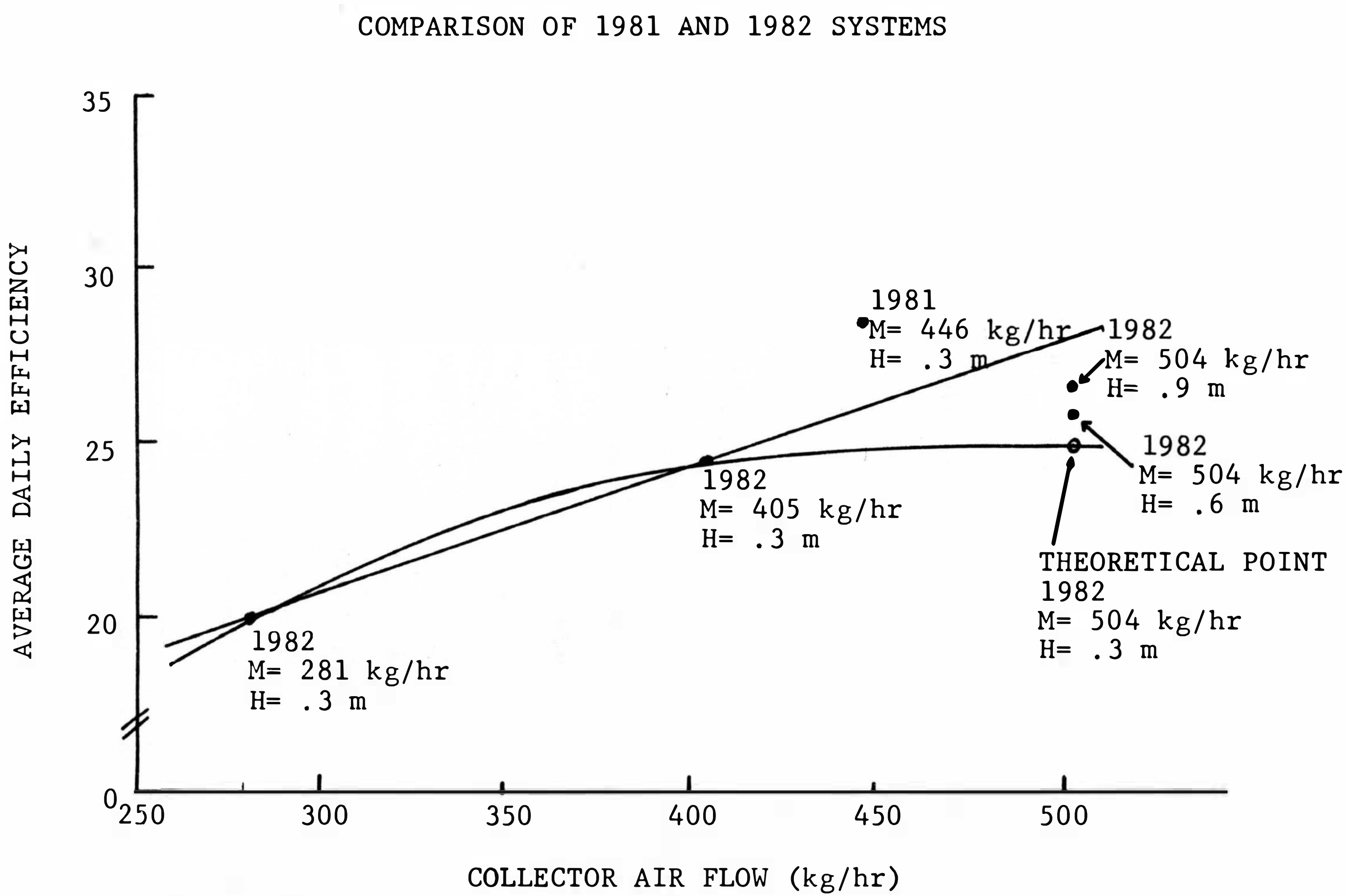

Figure 10: Average Daily System Efficiency versus Collector Air Flow Rate

storage elevations, as shown. A curvilinear relationship is then formed.

The efficiency of the 1981 system lies above both the linear and theoretical curvilinear extrapolation of the 1982 data. This suggests that the back-pass air flow pattern of the 1981 system is more efficient than the dual-pass air flow pattern of the 1982 system. This increase in system efficiency is approximately 3.5 percent over the linear extrapolation, or an approximate 14 percent improvement over the estimated performance of the 1982 system for the same collector air flow rate and storage elevation.

Stepwise multiple linear regression was used to evaluate the effects of variables (listed earlier in this section) on the daily energy collected for the 1982 system. The resulting prediction equations are given in Table 3 for the four different air flow rates and storage elevation combinations, along with corresponding coefficients of determination, computed f values and F values required at the .05 and .01 significance level. Table 4 summerizes the order in which the variables entered each regression analysis and in the following paragraphs the effects of the variables are discussed. The extent to which an independent variable is correlated to the dependent variable is indicated in the order in which it enters the stepwise regression. As each variable enters, the significance of the increase in the coefficient of determination is tested by the computed f value. If it is larger than the F value at a given level, then the equation is significant at that level.

Insolation entered all four equations first and was significant(.01) in all cases. In combination two, insolation was the only variable to enter. This is likely due to a large variation in insolation for the small number of observations, as compared to the variation in the other variables.

Daily average wind velocity entered combinations 1 and 3 in the second step and combination 4 in the third step. The addition of average wind velocity had only a significant(.05) effect in combination 1. This suggests that, at higher air flow rates and tank elevations, either the wind velocity had less effect on heat loss from the system or the variation in wind velocity, for combinations 3 and 4, was not great enough for the corresponding number of observations. At lower collector air flow rates the wind velocity will generally have a larger effect on system heat loss.

Ambient temperature, which directly affects heat loss from the system, entered combinations 1 and 3 third, and combination 4 last. In the first two cases its addition to the existing equation resulted in an equation significant at

TABLE 3

Prediction Equations for Daily Energy Collected

Combination	Step	Equation[1]	R^2	f	Required F .05	.01
1. M[2]=405 kg/hr H[3]=0.3 m	1	E= .2164I + 1.079	.9268	126.70	4.96	10.04
	2	E= .2257I - .6961Ws + 2.130	.9534	5.13	4.26	8.02
	3	E= .2180I - .7390Ws + .128Ta - .500	.9697	4.29	4.07	7.59
	4	E= .2253I - .8854Ws + .098Ta + .235Tt - 3.292	.9720	0.57	4.12	7.85
2. M=281 kg/hr H=0.3 m	1	E= .1955I + .083	.9957	233.20	161.40	4052.00
3. M=504 kg/hr H=0.6 m	1	E= .2415I + .937	.9184	56.25	6.61	16.26
	2	E= .2103I - .5801Ws + 4.718	.9632	4.87	6.94	18.00
	3	E= .2219I - .7207Ws + .171Ta + .214	.9917	10.33	9.28	29.46
	4	E= .2239I - .7181Ws + .211Ta - .130Tt + 1.005	.9922	0.13	19.25	99.25
4. M=504 kg/hr H=0.9 m	1	E= .2444I + 1.019	.9611	98.84	7.71	21.20
	2	E= .2754I - 1.216Tt + 15 738	.9763	1.93	9.55	30.82
	3	E= .2683I - .2707Ws - 1.4656Tt + 20.531	.9938	5.69	19.16	99.17
	4	E= .2674I - .3754Ws - .172Ta - .993Tt + 18.600	.9950	0.21	224.60	5625.00

1. E= daily energy collected, kWh
   I= daily energy available on collector surface, kWh
   Ws= daily average wind velocity, m/s
   Ta= daily average ambient temperature, C
   Tt= initial average water storage temperature, C
2. M= collector air flow rate
3. H= elevation of water storage tank above collector outlet

TABLE 4

Order of Variables for Daily Energy Collected

Combination	Insolation	Average Wind Velocity	Ambient Temperature	Initial Storage Temperature
1. M= 405 kg/hr H= 0.3 m	1**	2*	3*	4
2. M= 281 kg/hr H= 0.3 m	1*			
3. M= 504 kg/hr H= 0.6 m	1**	2	3*	4
4. M= 504 kg/hr H= 0.9 m	1**	3	4	2

**- significant at .01 level
* - significant at .05 level

the .05 level. In combination 4 ambient temperature was added to the equation but did not significantly(.05) affect the equation. The variation in ambient temperature was small for combination 4, which may explain this.

Initial storage temperature entered last in combinations 1 and 3 and second in combination 4. The variation in initial storage temperature was small in all three cases, failing to produce a significant improvement in the equations. Initial storage temperature is considered an important variable in the system performance, but during the test procedure the storage tank was filled with water at nearly the same temperature at the beginning of each test day. One day of data in combination 2 (August 13, 1982) was not included in the results because of an initial average storage temperature 5.6 degrees centigrade higher than the others. The daily average efficiency for this day was 10.3 percent, as compared to a 19.5 percent average for the other days in combination 2. This suggests the importance of initial average storage temperature, although more testing with varied initial storage temperatures is required to be conclusive.

Scatter diagrams and prediction equations for the daily energy collected versus insolation, for the four air flow rate and storage elevation combinations, are shown in Figures 11, 12, 13 and 14 with Figures 16 and 17 including the effects of daily average wind velocity for combinations 1 and 3, respectively. Figure 15 contains the four equations of Figures 11 through 14, along with an equation based on the combined data from the four individual equations. These equations were analyzed statistically to determine if the four individual equations were significantly different from the equation developed from the combined data. This was done by computing the amount of variation in the dependent variable explained by the variation in the independent variable for the four individual equations and comparing that to the same for the equation derived from the combined data. Analysis indicated that the four individual equations are significantly(.01) different from the equation derived from the combined data, and that daily energy collected cannot be predicted using a single equation when different collector air flow rates and storage elevations are used.

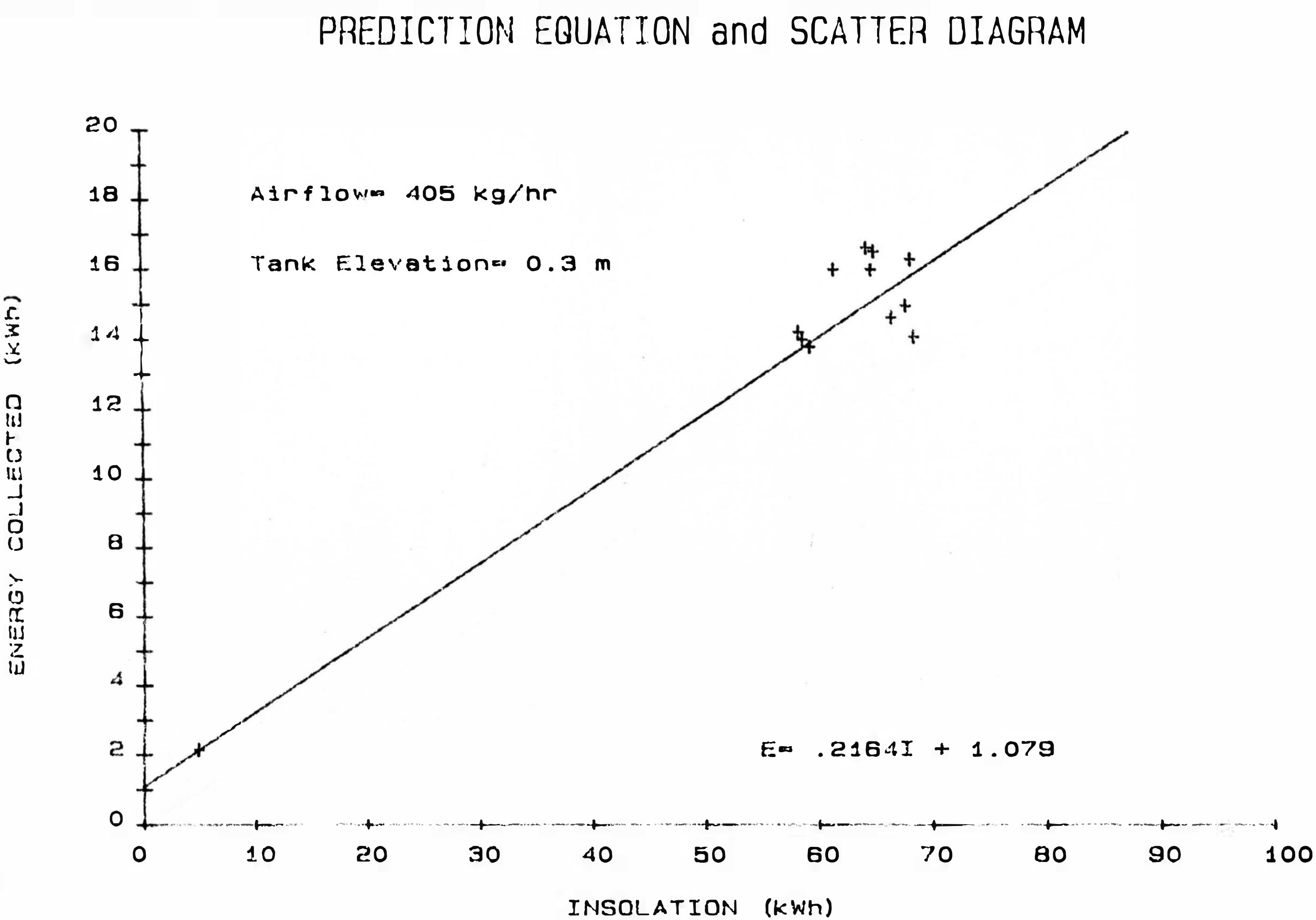

Figure 11: Daily Energy Collected versus Daily Insolation for a Collector Air Flow of 405 kg/hr and a Tank Elevation of 0.3 m

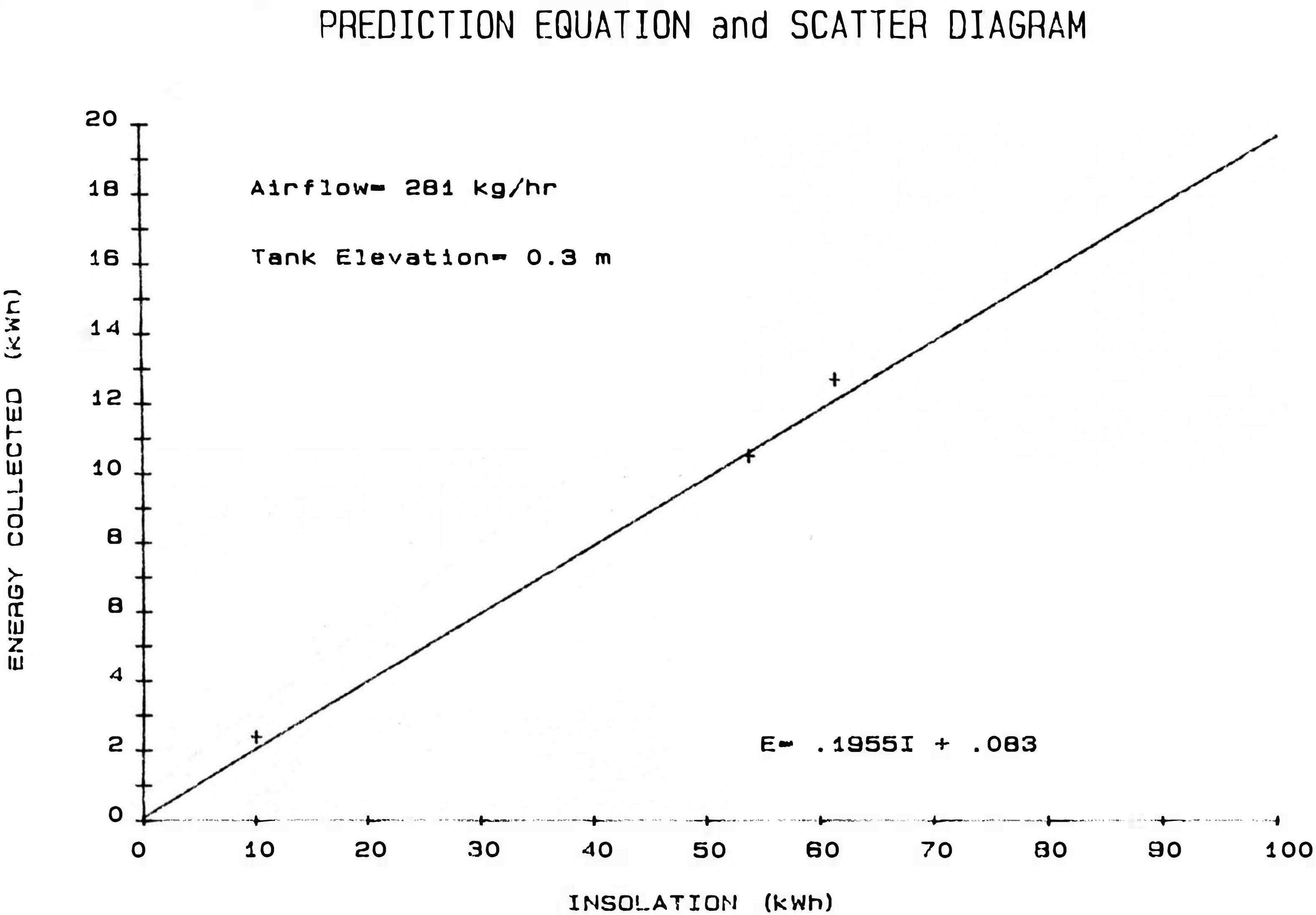

Figure 12: Daily Energy Collected versus Daily Insolation for a Collector Air Flow of 281 kg/hr and a Tank Elevation of 0.3 m

PREDICTION EQUATION and SCATTER DIAGRAM

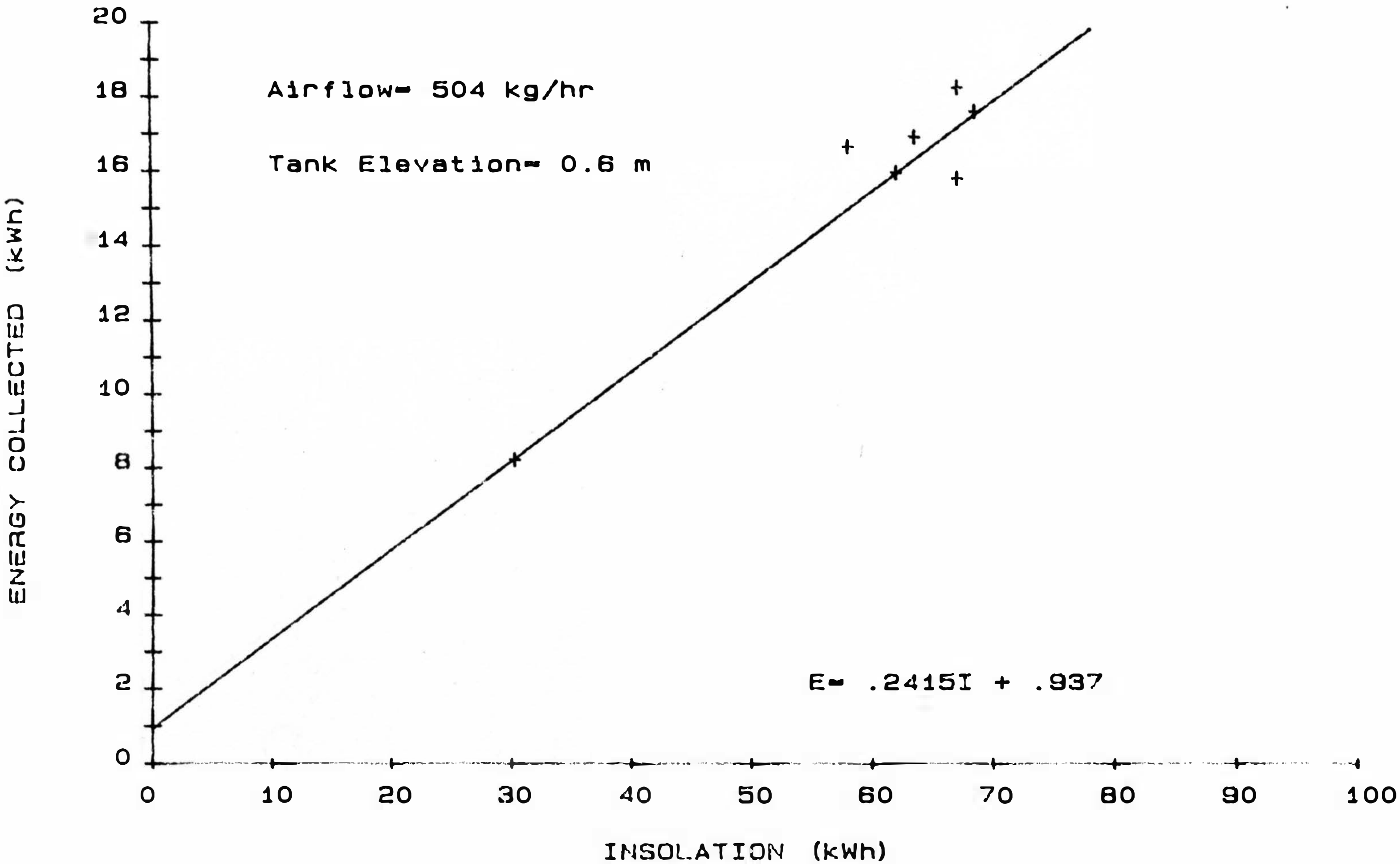

Figure 13: Daily Energy Collected versus Daily Insolation for a Collector Air Flow of 504 kg/hr and a Tank Elevation of 0.6 m

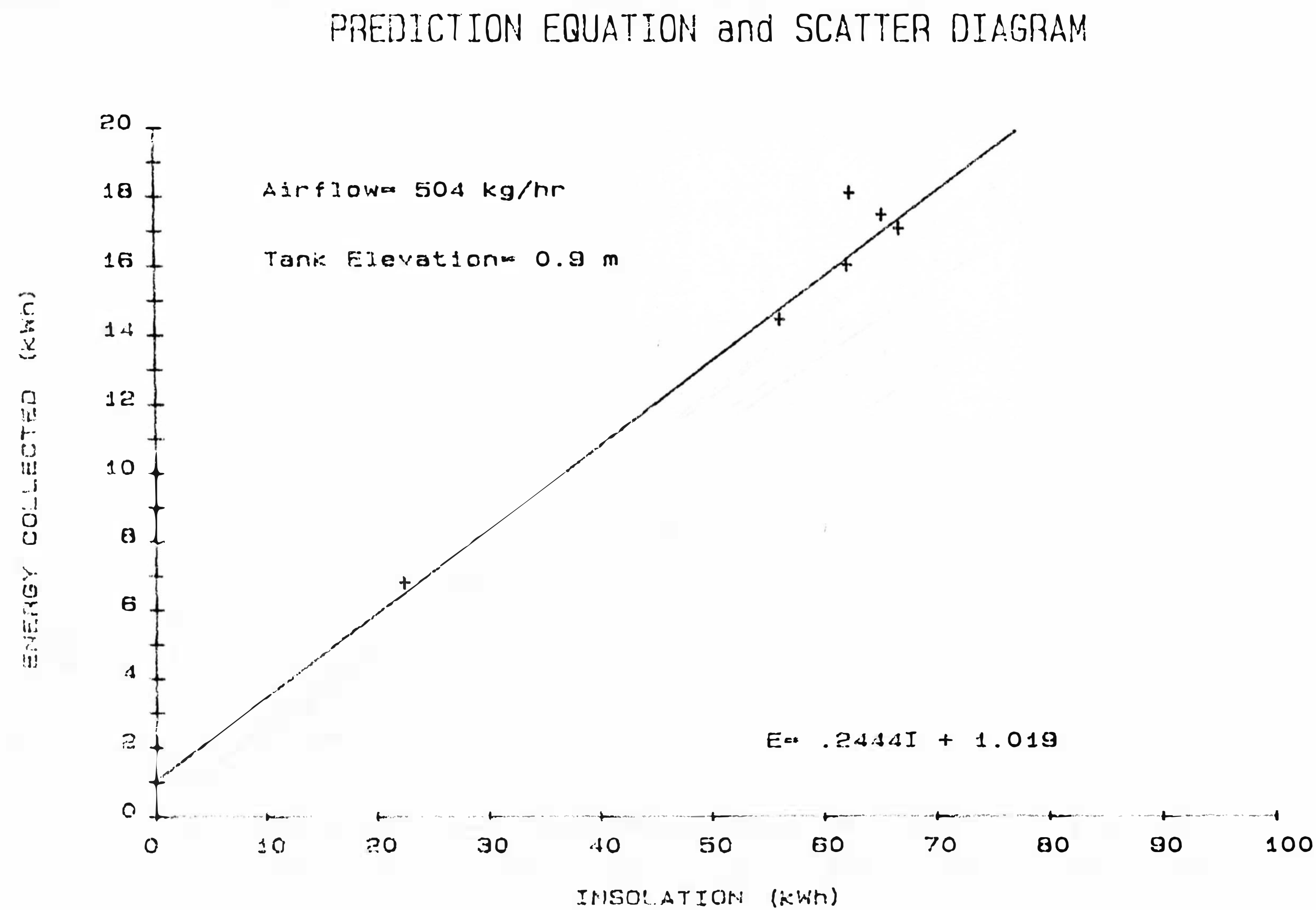

Figure 14: Daily Energy Collected versus Daily Insolation for a Collector Air Flow of 504 kg/hr and a Tank Elevation of 0.9 m

Daily Energy Collected versus Insolation

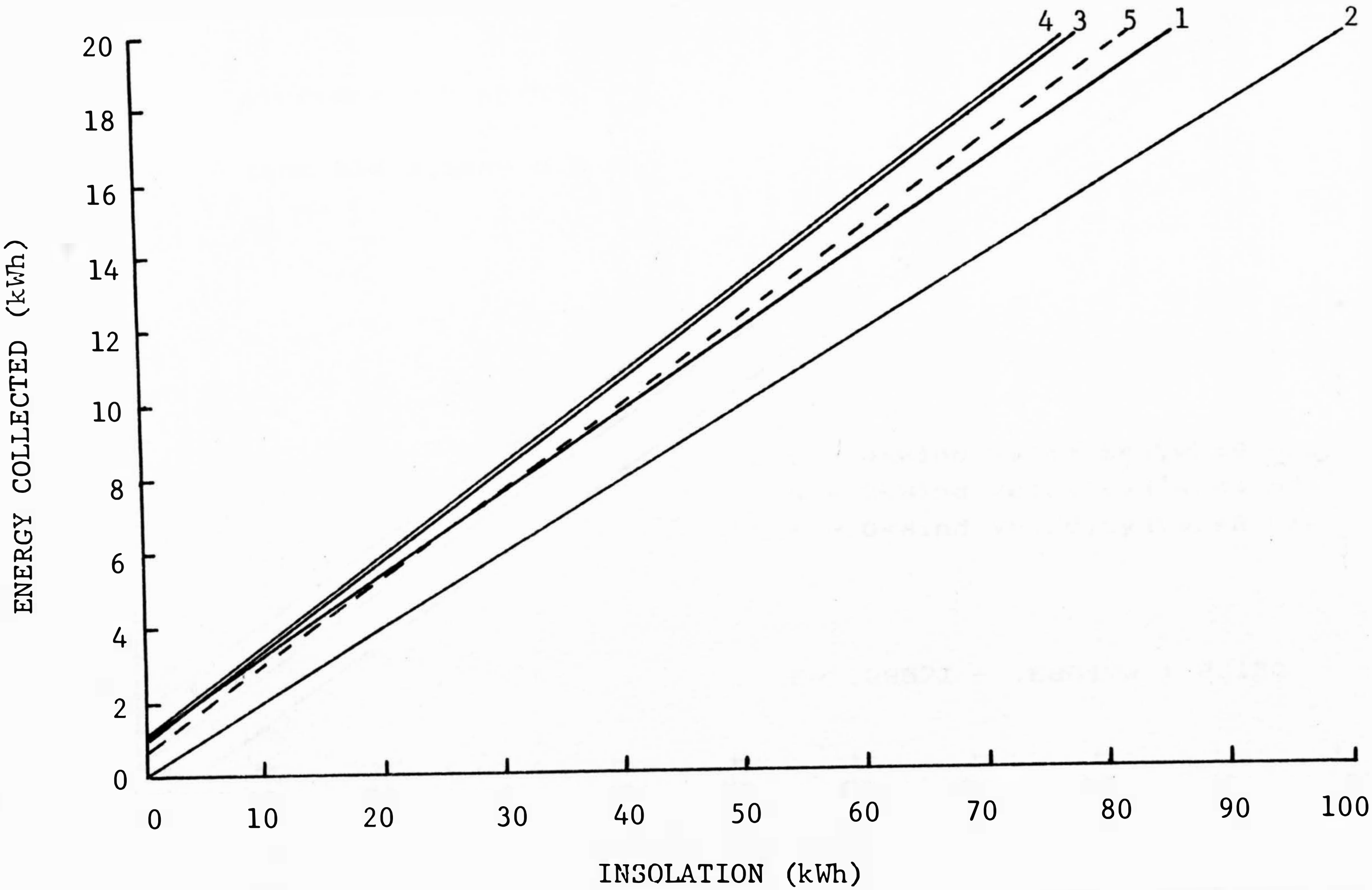

Figure 15: Individual and Combined Prediction Equations

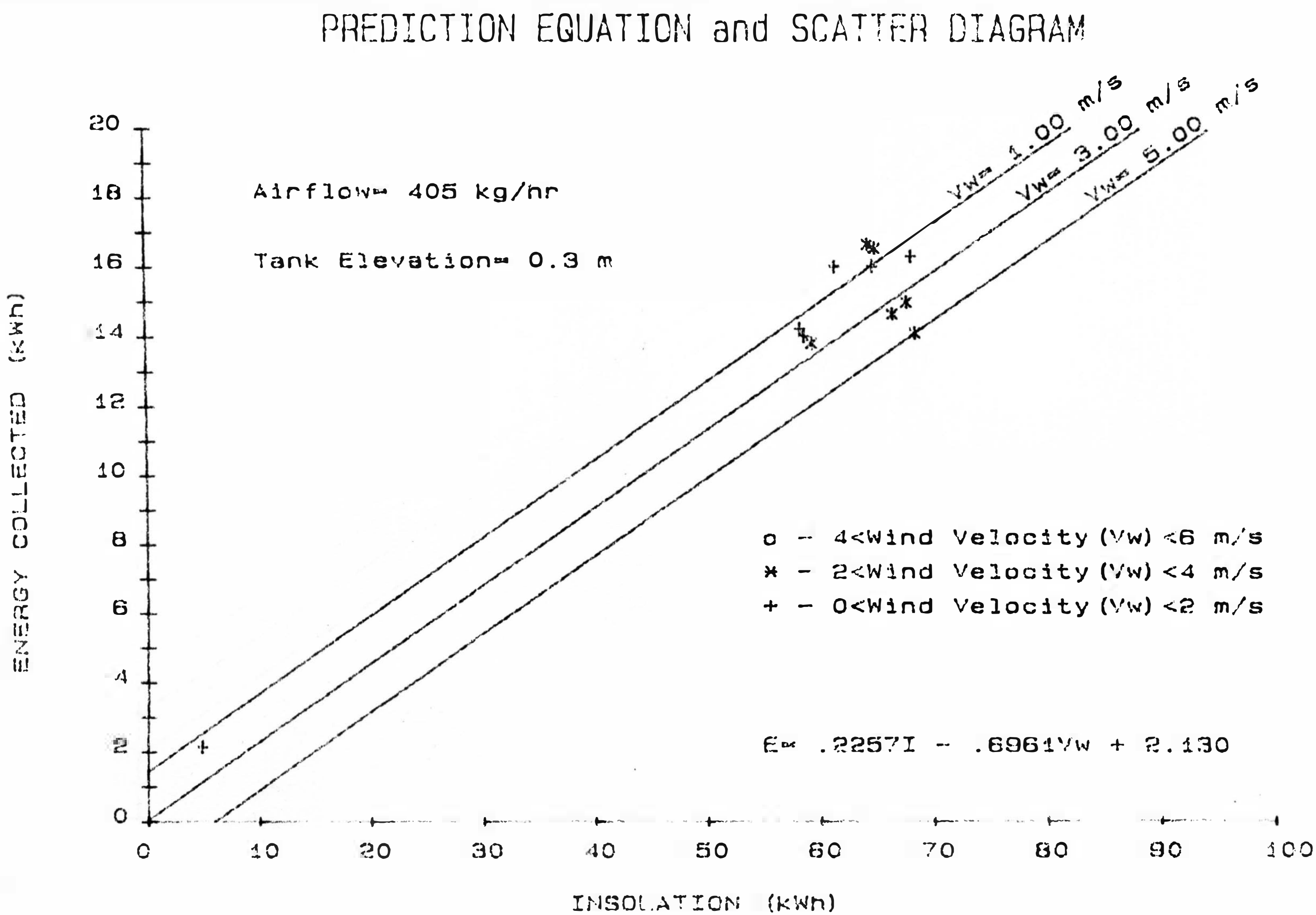

Figure 16: Daily Energy Collected versus Daily Insolation and Average Wind Velocity for a Collector Air Flow of 405 kg/hr and a Tank Elevation of 0.3 m

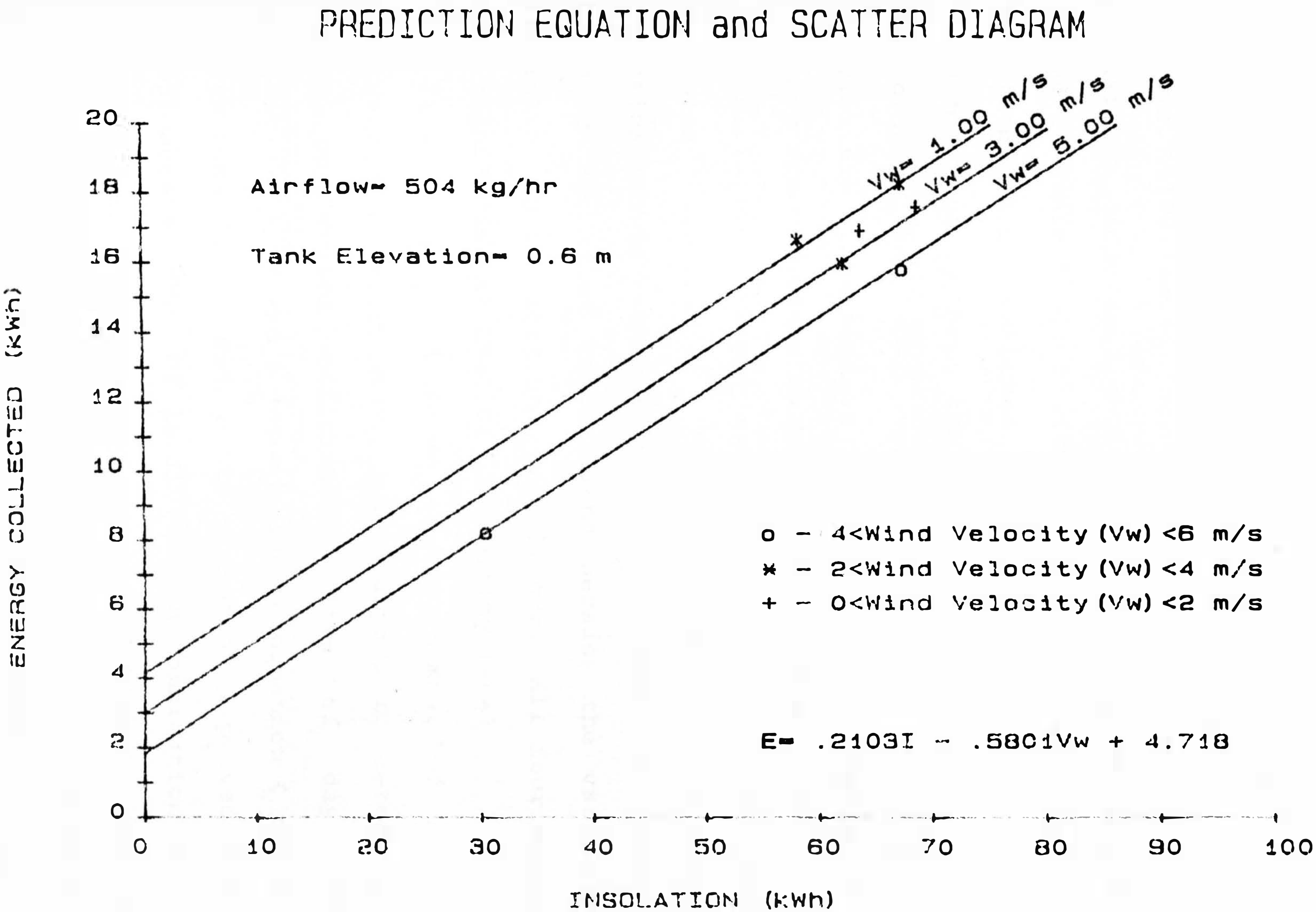

Figure 17: Daily Energy Collected versus Daily Insolation and Average Wind Velocity for a Collector Air Flow of 504 kg/hr and a Tank Elevation of 0.6 m

Hourly Energy Collected

The 1982 system was analyzed and prediction equations were developed for the energy collected during a 30 minute interval. (Variables included in the analyses are listed earlier in this section.) The resulting equations are listed in Table 5 along with each corresponding coefficient of determination, computed f value and F value required to be significant at both the .05 and .01 probability level. The orders that each variable entered the regression analyses are summarized in Table 6, and the effects of each variable are discussed in the following paragraphs.

Insolation entered each air flow rate and storage elevation combination first. The coefficient of determination in combination 2 is substantially larger than those of the other combinations because the variation in insolation in combination 2 was larger. All four equations were significant at the .01 probability level.

Time of day, in terms of the number of 30 minute intervals from solar noon, was analyzed to determine its effect on system efficiency. Time of day entered combinations 1, 2 and 3 second, and combination 4 third. In combinations 1, 3, and 4 its inclusion improved equation significance at the .01 level, and in combination 2 at the .05 level. The large variation in insolation in combination 2, as compared to the other combinations, makes it difficult to recognize the effects of the other variables.

TABLE 5

Prediction Equations for Hourly Energy Collected

Combination	Step	Equation[1]	R^2	f	Required F .05	Required F .01
1. M[2]=405 kg/hr H[3]=0.3 m	1	E= .2446I - .049	.8447	772.56	3.92	6.85
	2	E= .2220I - 380.2h + .230	.8948	67.02	3.07	4.09
	3	E= .2130I - 372.7h + .010Ta + .011	.9050	15.02	2.68	3.95
	4	E= .2134I - 316.6h + .015Ta - .016Tw + .118	.9131	12.94	2.45	3.48
2. M=281 kg/hr H=0.3 m	1	E= .1993I - .006	.9394	526.69	4.17	7.56
	2	E= .1971I - 145.1h + .066	.9473	4.96	3.32	5.39
	3	E= .1593I - 134.7h + .018Ta - .233	.9535	4.29	2.92	4.51
	4	E= .1609I - 146.3h + .013Ta + .026Tw - .463	.9538	0.16	2.69	4.02
3. M=504 kg/hr H=0.6 m	1	E= .2951I - .190	.7744	281.50	4.00	7.08
	2	E= .2130I - 750.0h + .460	.9089	119.68	3.15	4.98
	3	E= .2288I - 708.6h - .008Tw + .582	.9152	5.86	2.76	4.13
	4	E= .2365I - 623.8h + .009Ta - .012Tw + .341	.9192	3.92	2.53	3.65
4. M=504 kg/hr H=0.9 m	1	E= .2574I + .018	.7537	214.20	4.00	7.08
	2	E= .2806I - .033Tw + .413	.8843	77.85	3.15	4.98
	3	E= .2558I - 337.6h - .027Tw + .593	.9025	12.72	2.76	4.13
	4	E= .2483I - 313.7h + .011Ta - .030Tw + .412	.9041	1.13	2.53	3.65

1. E= energy collected during 30 minute interval, kWh
   I= energy available on collector surface during 30 minute interval, kWh
   h= number of 30 minute intervals from solar noon; ex. 11:00, h=1; 2:30, h=2.5
   Ta= ambient temperature at beginning of 30 minute interval, C
   Tw= temperature of water entering collector at beginning of 30 minute interval, C
2. M= collector air flow rate
3. H= elevation of water storage tank above collector outlet

TABLE 6

Order of Variables for Hourly Energy Collected

Combination	Insolation	Time of Day	Ambient Temperature	Temperature of Water Entering Collector
1. M= 405 kg/hr H= 0.3 m	1**	2**	3**	4**
2. M= 281 kg/hr H= 0.3 m	1**	2*	3*	4
3. M= 504 kg/hr H= 0.6 m	1**	2**	4**	3**
4. M= 504 kg/hr H= 0.9 m	1**	3**	4	2**

**- significant at .01 level
* - significant at .05 level

Ambient air temperature entered combinations 1 and 2 third, and combinations 3 and 4 last. This may indicate that the highest collector air flow rates lost less energy to the environment, thus being less affected by it. Also, there was less variation in ambient temperature in combinations 3 and 4.

Temperature of the water entering the collector was last to enter combinations 1 and 2, third to enter combination 3 and second to enter combination 4. This may indicate that at higher collector air flow rates and increasing tank elevations, the energy collected by the system is affected more by the incoming water temperature than hour angle and ambient temperature. In combination 2 the addition of incoming water temperature was not significant, which suggests that at low air flow rates the heat loss from the system is large and has more effect on system performance than incoming water temperature.

Output Water Temperature

Prediction equations for the temperature of the water leaving the collector, at the end of a 30 minute interval, are given in Table 7 for each air flow and tank elevation combination. Table 8 summarizes the order in which the variables entered the reqression analyses. (The variables used are listed at the beginning of this section.) Insolation is in terms of the energy available during the previous 30 minutes, although the output water temperature is directly related to the intensity of the instantaneous solar radiation. The use of energy available during the previous 30 minutes is justifiable because it is a measure of the average solar radiation intensity, which usually does not change substantially over a 30 minute period.

Insolation entered the stepwise regression first in all combinations except 3, where average tank temperature entered first. In this case, the average tank temperature was more closely correlated to the water output temperature than was insolation. Average tank temperature entered second in combinations 1, 2 and 4, indicating good correlation between average tank temperature and water output temperature. It may be that insolation is more highly correlated to water output temperature early in the day, while average tank temperature is more highly correlated later in the day. Early in the day water output temperature increases rapidly with increasing insolation, while later , when insolation is decreasing, the water output temperature does not decrease, and sometimes increases. This is due to the higher water temperature needed to maintain thermosyphonic flow as recycling begins and the water temperature entering the collector is higher than earlier in the day.

TABLE 7

Prediction Equations for Output Water Temperature

Combination	Step	Equation[1]	R^2	f	Required F .05	Required F .01
1. M[2]=405 kg/hr	1	Two= 4.152I + 22.1	.7384	400.74	3.92	6.85
H=0.3 m	2	Two= 3.110I + .440Tt + 16.0	.9296	382.97	3.07	4.79
	3	Two= 3.356I + .328Tt + .417Tw + 11.6	.9383	19.78	2.68	3.95
2. M=281 kg/hr	1	Two= 3.830I + 20.1	.9466	603.05	4.17	7.56
H=0.3 m	2	Two= 3.053I + .274Tt + 15.4	.9869	101.46	3.32	5.39
	3	Two= 2.863I + .274Tt + 1.294Tw + 1.0	.9886	4.70	2.92	4.51
3. M=504 kg/hr	1	Two= .553Tt + 29.0	.6158	131.43	4.00	7.08
H=0.6 m	2	Two= 2.636I + .375Tt + 17.5	.9285	354.30	3.15	4.98
	3	Two= 3.015I + .352Tt + .330Tw + 14.2	.9453	24.53	2.76	4.13
4. M=504 kg/hr	1	Two= 3.527I + 24.2	.7062	168.26	4.00	7.08
H=0.9 m	2	Two= 2.522I + .439Tt + 17.9	.9356	245.68	3.15	4.98
	3	Two= 2.730I + .246Tt + .330Tw + 16.6	.9580	36.31	2.76	4.13

1. Two= temperature of water leaving collector at the end of a 30 minute interval, C
   I= average insolation over 30 minute interval, kW
   Tt= average water storage temperature at beginning of 30 minute interval, C
   Tw= temperature of water entering collector at beginning of 30 minute interval, C
2. M= collector air flow rate
   H= elevation of water storage tank above collector outlet

TABLE 8

Order of Variables for Output Water Temperature

Combination	Insolation	Average Tank Temperature	Temperature of Water Entering Collector
1. M= 405 kg/hr H= 0.3 m	1^{**}	2^{**}	3^{**}
2. M= 281 kg/hr H= 0.3 m	1^{**}	2^{**}	3^{*}
3. M= 504 kg/hr H= 0.6 m	2^{**}	1^{**}	3^{**}
4. M= 504 kg/hr H= 0.9 m	1^{**}	2^{**}	3^{**}

**- significant at .01 level
* - significant at .05 level

Incoming water temperature entered all combinations last because throughout most of the day, until storage recycling began, it remained fairly constant. Also, every day of data in each combination was started with average water storage temperatures in a narrow range, providing similar incoming water temperatures in each. One day of data (August 8, 1982) in combination 2, which was not included in the analysis, had an initial water storage temperature about 5.6 degrees centigrade higher than the other three days analyzed in this combination. Inclusion of this day in the regression analysis causes the coefficient for incoming water temperature in the prediction equation for combination 2, shown below, to become negative. This indicates that at a higher temperature, the incoming water picks up less heat causing a smaller temperature rise in the incoming water.

$$Two = 2.882I - .920Tw + .518Tt + 57.9$$

Time of day was not used as a variable in this analysis because it is related to the average water storage temperature, which varied similarly in each combination on days with similar insolation. Figure 18 illustrates how the average water storage temperature varied throughout the day on similar insolation days in each combination. The incoming water temperature is also included, and both are adjusted for initial temperature differences of 2 to 3 degrees centigrade.

The adjusted water storage temperature, when multiplied by the water mass in the storage tank and the specific heat of water, is a direct measure of the energy collected at any time during the day. The highest collector air flow rate and highest storage elevation collected the most energy, with the lowest air flow rate and tank elevation collecting the least.

The incoming water temperature reflects the amount of time required for the water to cycle through the storage one time. As shown in Table 9, the shortest recirculation time occurred in combination 4, while the longest was in combination 2. The average flow rate, in kilograms per hour, required to circulate the 450 kilograms of water above the storage outlet, is also shown.

Figure 18 also illustrates that the incoming water temperature approaches the average tank temperature more quickly in combination 4, indicating a more uniform water storage temperature.

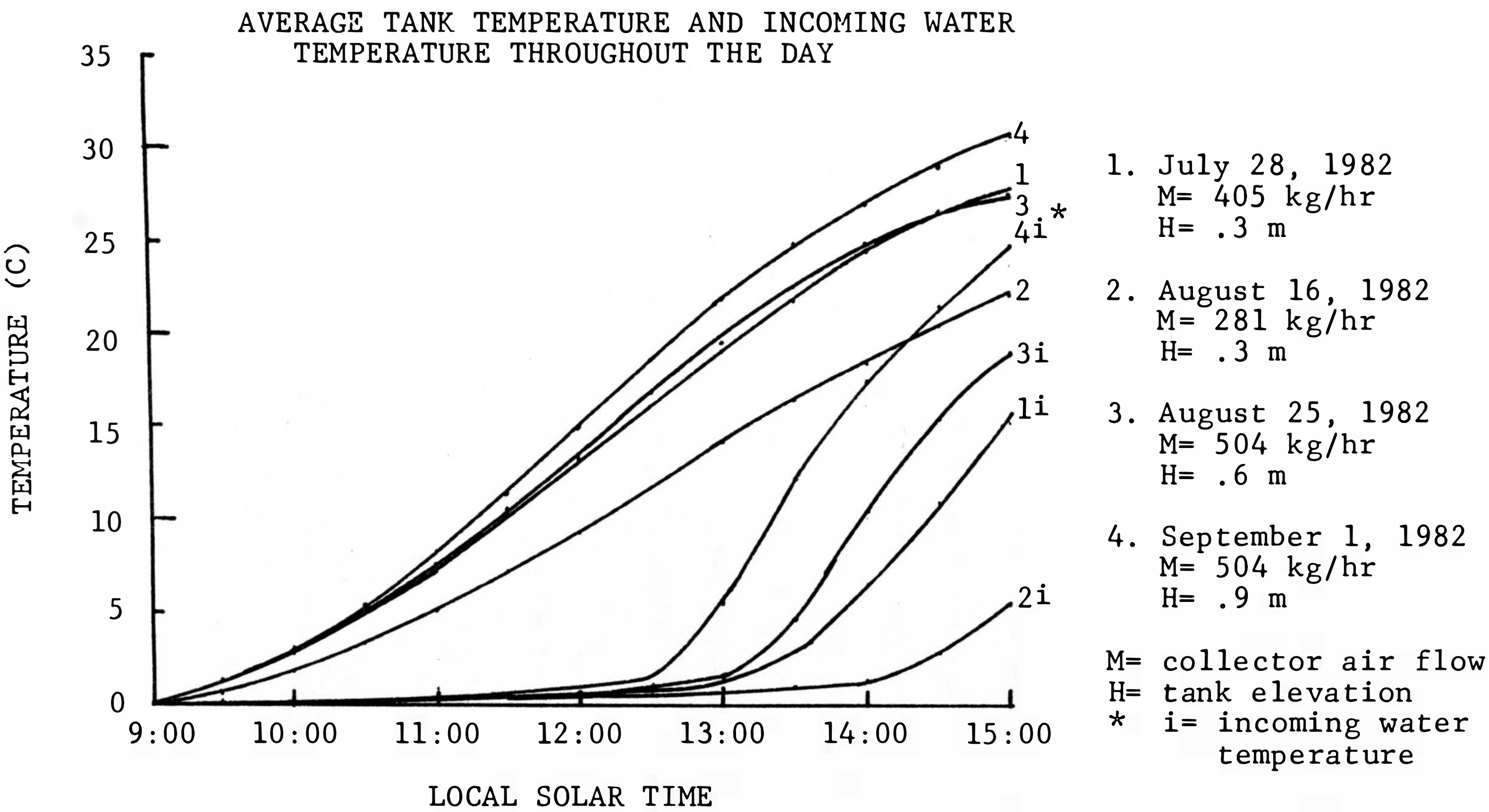

Figure 18: Average Tank Temperature and Incoming Water Temperature as a Function of Time of Day

TABLE 9

Water Storage Recycling Time and Average Flow Rate

Combination	Recycling Time(hr)	Average Flow Rate(kg/hr)
1	4.0 - 4.5	101 - 113
2	5.0 - 5.5	82 - 91
3	3.5 - 4.0	114 - 130
4	3.0 - 3.5	130 - 151

Figures 19 to 22 show the temperatures in the water storage tank, at 14 equally spaced levels, every 30 minutes for each of the four days illustrated in Figure 17. The storage outlet was located between levels 1 and 2, explaining why level one changes temperatures only slightly throughout the day. The water below the outlet is not circulated and increases in temperature due to conduction only. At higher collector air flow rates and storage elevations, the water storage temperatures are more uniform at the end of the day, indicating less storage stratification at the higher water flow rates.

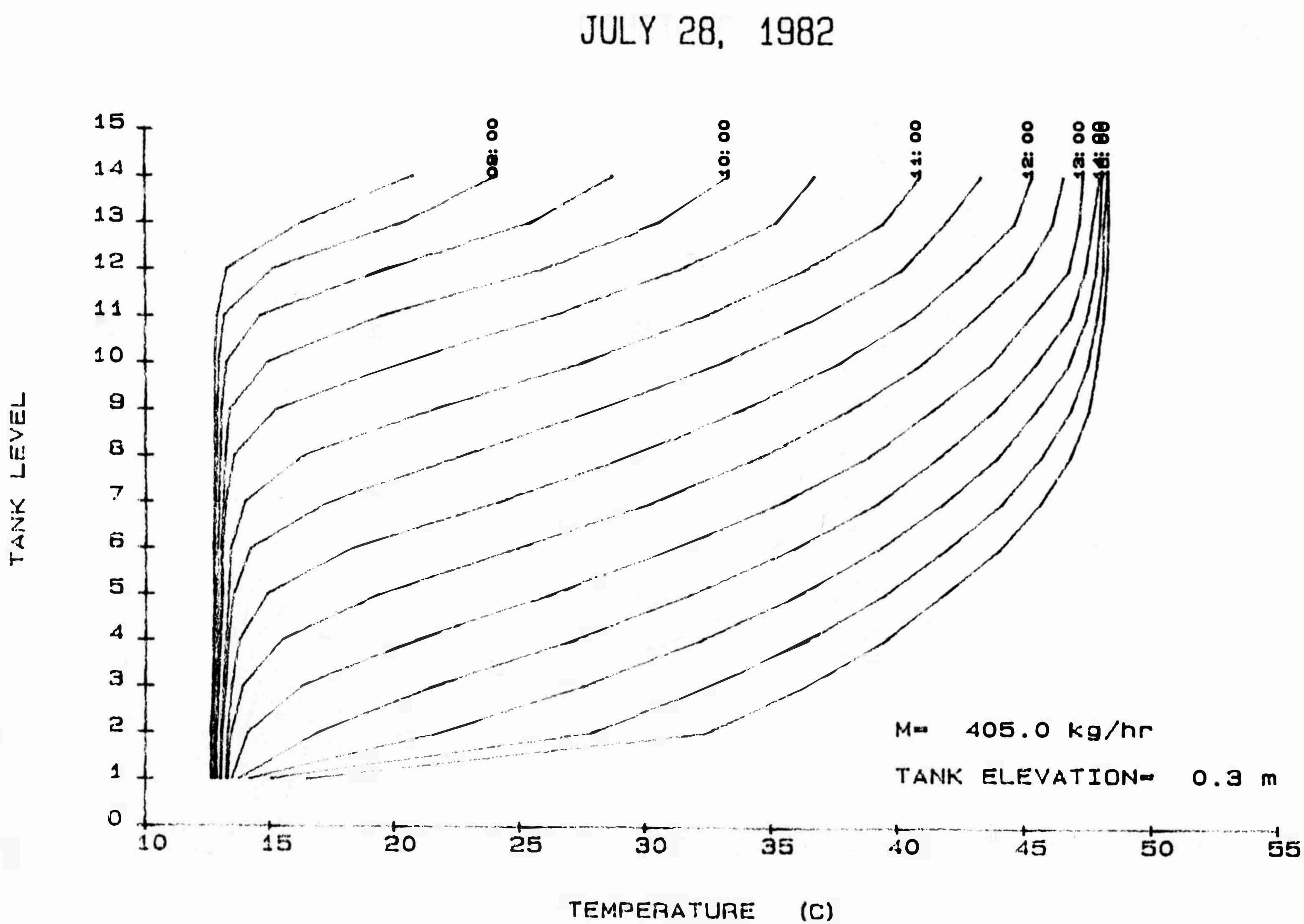

Figure 19: Water Storage Temperature Distribution for a Collector Air Flow of 405 kg/hr and a Tank Elevation of .3 m

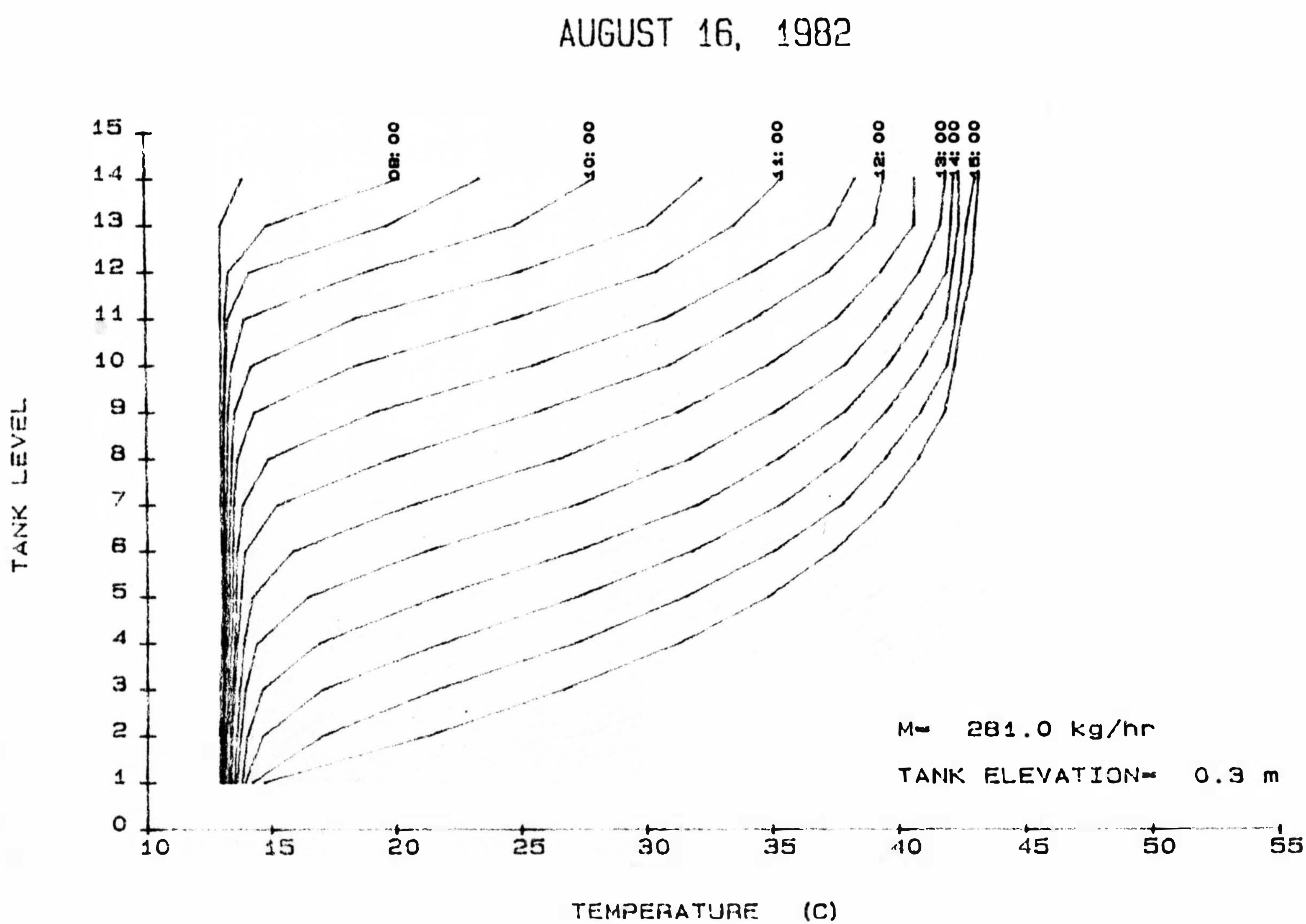

Figure 20: Water Storage Temperature Distribution for a Collector Air Flow of 281 kg/hr and a Tank Elevation of .3 m

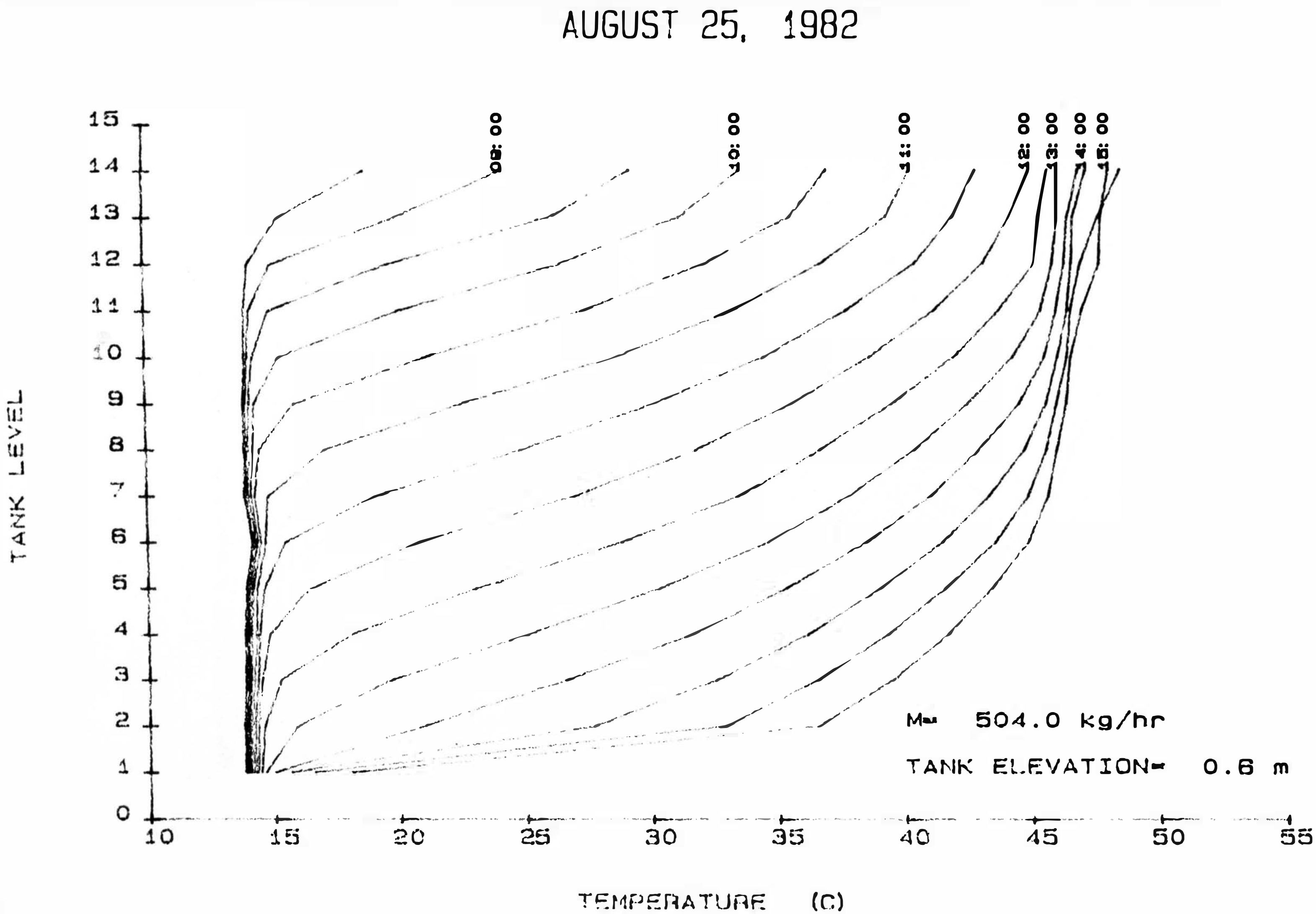

Figure 21: Water Storage Temperature Distribution for a Collector Air Flow of 504 kg/hr and a Tank Elevation of .6 m

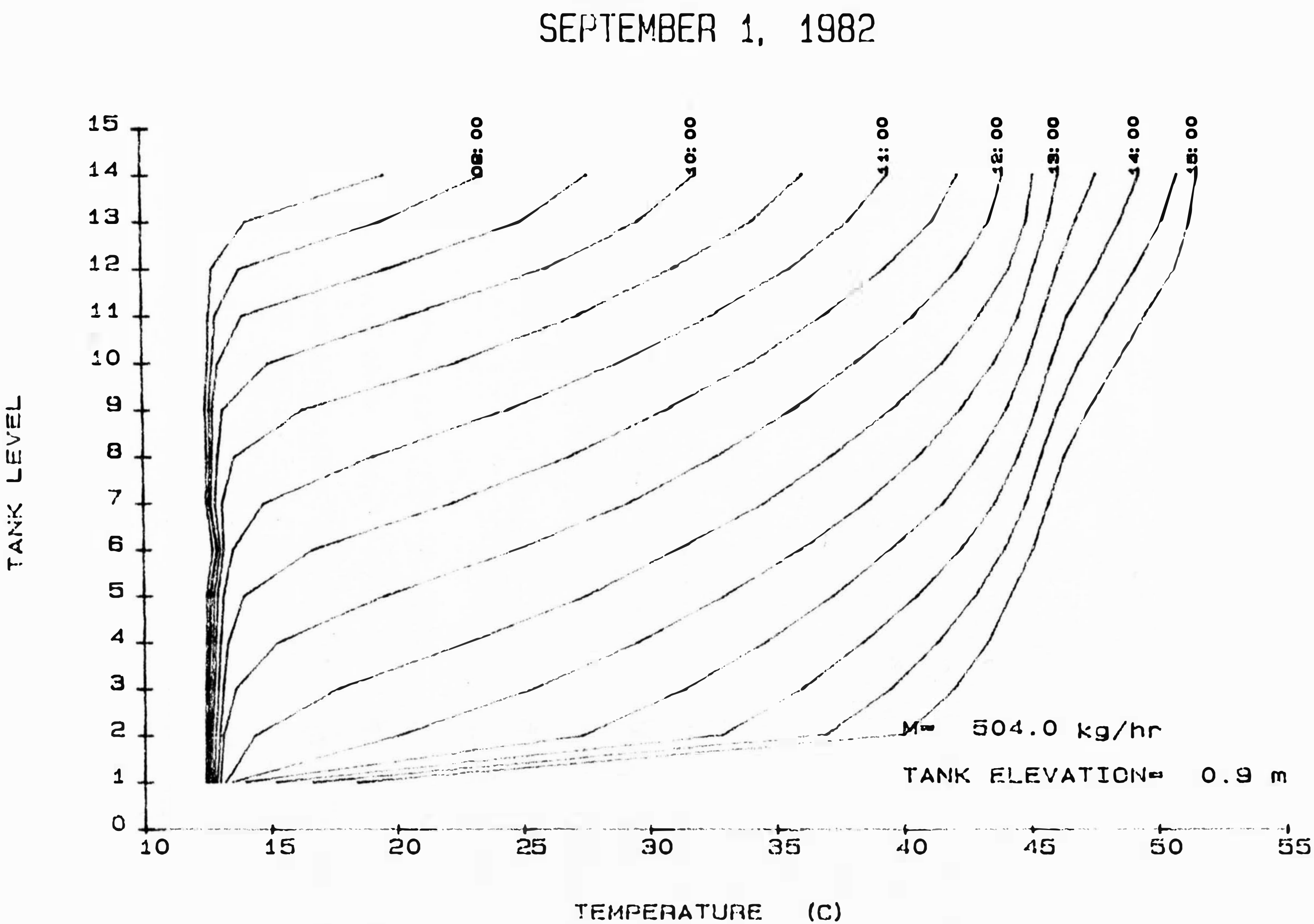

Figure 22: Water Storage Temperature Distribution for a Collector Air Flow of 504 kg/hr and a Tank Elevation of .9 m

Interpretation of Experimental Results

The previous sections analyze the 1981 and 1982 solar water heating systems in terms of percent efficiency, daily and hourly energy collected and output water temperature. Additional information, which is valuable for evaluating the solar water heating concept and for selecting the best design from among those analyzed, is provided in this section. Table 10 summarizes the average performance of each system in terms of average daily water storage temperature rise, average length of collecting day and average total insolation striking the collector surface.

The performance of each system is normalized for comparison in columns six and seven. Column six is the average temperature rise of the 0.45 cubic meter water storage per square meter of collector. Column seven is the average temperature rise of the 0.45 cubic meter water storage per square meter of collector per average kilowatt of insolation striking the collector. The average insolation, in kilowatts, is the daily insolation measured during the collector operation period divided by the total time of collector operation.

From column six it appears that the 1981 system did not perform as well as the comparable 1982 system (M= 405 kg/hr and H= 0.3 m) in terms of temperature rise in the 0.45 cubic meter water storage per square meter of collector. One

TABLE 10

Average Performance of 1981 and 1982 Systems

System	Ti[1] (C)	Tf[2] (C)	D-T[3] (C)	Time[4] (hr)	Insolation[5] (kWh)	VT/A[6] (m^3C/m^2)	VT/I[7] (m^3C/m^2)
1981 M=446 kg/hr H=0.3 m	17.7	40.4	22.7	5.25	45.76	.6856	1.172
1982 M=405 kg/hr H=0.3	13.8	41.1	27.3	6.50	64.22	.8245	1.243
M=281 kg/hr H=0.3 m	13.3	34.2	20.9	6.50	58.12	.6312	1.052
M=504 kg/hr H=0.6 m	13.8	43.7	29.9	6.50	64.89	.9030	1.348
M=504 kg/hr H=0.9 m	12.9	42.4	29.5	6.50	63.15	.8909	1.366

1. Ti= average initial storage temperature
2. Tf= average final storage temperature
3. D-T= average change in storage temperature throughout day
4. Time= average length of collecting day
5. Insolation= total energy available on collector surface throughout day
6. VT/A= temperature rise in storage volume per square meter of collector
7. VT/I= temperature rise in storage volume per kilowatt of insolation(square meter basis)

explanation for this may be that insolation in 1981 averaged 73 percent of that in 1982. This alone would tend to reduce the temperature rise in the water storage. Another factor is that the 1981 system averaged 5.25 hours of running time per day versus 6.50 hours for the comparable 1982 system. With average insolation and average collector running time taken into account in column seven, it still appears as though the 1981 system did not perform as well as the comparable 1982 system. If the energy collected by the 1981 system is revised upward proportional to the increased solar energy which was available in 1982 (1981 insolation was approximately 90 percent of the measured insolation of the comparable 1982 system), the value in column seven for the 1981 system increases to 1.302 cubic meters-degrees centigrade per kilowatt. With this adjustment, which approximates the 1981 system performance for the same insolation level as the 1982 system, the 1981 system's performance appears 5 percent more efficient than the comparable 1982 system.

Higher efficiency for the 1981 system, with all other factors the same, could be expected because the literature suggests that a back-pass only system is more efficient than a single-glazed, front and back-pass system for moderate and high temperature applications. The back-pass only method offers another advantage, which is a simpler, less expensive collector to build. From the results discussed, it appears that the back-pass air flow would be desirable for the system.

Other design recommendations include an air flow rate of 33.8 kilograms per hour per square meter of collector (corresponding to 504 kilograms per hour in the 1982 system), and an elevation difference of 0.6 meters between the top of the heat exchanger and the bottom outlet on the storage tank. Results of the 1982 analyses indicate that the higher air flow rate and tank elevation can increase efficiency approximately 22 and 3 percent, respectively, and these do not involve proportionally that much added cost.

During the year, the water heating package would most likely be used for approximately 180 days, from April 1 to September 30. Using monthly averages for insolation available on a 60 degree surface, approximately 1060 kilowatt-hours of energy are available per heating season per square meter of collector. With the system operating under the conditions discussed earlier, an average temperature rise of 2.23 degrees centigrade would be provided in the 0.45 cubic meters of water storage per square meter of collector per day. Throughout the heating season, assuming an operating efficiency of 25.8 percent, approximately 273 kilowatt-hours of energy would be collected per square meter of collector. At 0.05 dollars per kilowatt-hour, a savings of 13.65 dollars per square meter of collector per year in energy costs would result, assuming 100 percent utilization of the collected energy.

CONCLUSIONS

Research was conducted at South Dakota State University to develop and evaluate a solar water heating package for the SEI-TES system. The system was tested with air flow behind the absorber plate only in 1981 and air flow on both sides of the absorber plate in 1982. The 1982 system was tested at different combinations of air flow rate and storage elevation to determine their effects on system efficiency. The following conclusions were reached as a result of this study:

1. The SEI-TES system can be effectively utilized to heat water using an air-to-water heat exchanger, a raised storage tank and thermosyphonic flow.

2. The 1981 back-pass system was more efficient than the 1982 system when compared at the same collector air flow rate and storage elevation.

3. For the different collector air flow rate and storage elevation combinations, the 1982 system efficiencies were:

   Airflow= 405 kg/hr, elevation= .3 m   Eff= 24.5%
   Airflow= 281 kg/hr, elevation= .3 m   Eff= 20.0%
   Airflow= 504 kg/hr, elevation= .6 m   Eff= 25.8%
   Airflow= 504 kg/hr, elevation= .9 m   Eff= 26.5%

4. Collector air flow rate had more effect on system efficiency than tank elevation.

5. A prediction equation for system efficiency for the 1982 system using collector air flow rate(Mair), insolation(I) and average wind velocity(Vw) was developed.

   $$Eff = 20.69 + .357Mair - .1475I - 1.013Vw$$

6. Prediction equations for daily energy collected were developed for the 1982 system for each collector air flow rate and tank elevation combination using insolation, wind velocity, average ambient temperature and initial water storage temperature as variables(Table 3).

7. Prediction equations were developed for hourly energy collected for the 1982 system for each air flow rate and storage elevation combination using insolation, sun hour angle, ambient air temperature and temperature of the water entering the collector as variables(Table 5).

8. Prediction equations were developed for output water temperature for the 1982 system for each collector air flow rate and storage elevation using insolation, average storage temperature and incoming water temperature as variables(Table 7).

REFERENCES

1. Adams, K. L. 1980. Effect of supplemental heat for nursing piglets, Journal of Animal Science 53:1424-31.

2. Baughn, James W. 1977. Experimental investigation and computer modeling of a solar natural circulation system, Proceedings of the Annual Meeting of the American Section of the International Solar Energy Society, Orlando, Florida, June 16-19, Section 4 Session D.2, 5pp.

3. Baughn, James W. and Douglass A Dougherty. 1978. Experimental study of storage elevation in a thermosyphon hot water system, Proceedings of the Annual Meeting of the American Section of the International Solar Energy Society, Inc.:Solar Diversification, Denver, Colorado, August 28-31 volume 2.2, pp. 36-40.

4. Brewer, Robert N. 1981. Solar Applications in Agriculture. The Franklin Institute Press, Philadelphi, Pennsylvania, 143 pp.

5. Butler, James L. 1980. On-farm applications of solar energy, Proceedings of the Annual Meeting of the American Section of the International Solar Energy Society, Phoenix, Arizona, June, volume 3.1, pp.11-15.

6. Hayden, M. B. and P. D. Thompson. 1976. Solar thermal energy utilization in the milking parlor, Proceedings of Symposium on use of Solar Energy for Poultry and Livestock Production, November 9-10, Auburn, Alabama, pp. 181-195.

7. Healy, Steve. 1981. Design of a mathematical model for a solar water pre-heater system, Report for Mechanical Engineering Lab 3, SDSU, Brookings, South Dakota, 27 pp.

8. Heber, Albert J., Mylo A. Hellickson and Lalit Verma. 1982. SEI-TES: Solar heating for swine housing, Transactions of the ASAE, 25(6);1680-1684.

9. Heid, Walter G., Jr. and Warren K. Trotter. 1982. Progress of solar technology and potential farm uses, National Economics Division, ERS-USDA, Agricultural Economic Report No. 489.

10. Hellickson, Martin L. 1980. Solar and waste heat tempered water for milking parlors, Department of Agricultural Engineering, Oregon State University, Corvallis.

11. Hellickson, Mylo A., Lesli L. Christianson and Albert J. Heber. 1981. Multi-use solar energy intensifier-thermal energy storage system performance, ASAE Paper No. 81-4555, ASAE, ST. Joseph, Michigan 49085.

12. Henderson, S. M. and R. L. Perry. 1981. Agricultural Process Engineering. AVI Publishing Co., Westport, Connecticut, 442 pp.

13. Kays, W. M. and A. L. London. 1964. Compact Heat Exchangers, 2nd Edition. McGraw Hill Book Company, New York, New York, 156 pp.

14. Kline, G. L. 1980. Solar collectors for multiple-use applications on farms, USDA, Science and Education Administration, Agricultural Research, Ames, Iowa, 6 pp.

15. Kocher, Michal F., Gerald R. Bodman and Merlyn Lay. 1981. Solar grain drying and farrowing house heating with a multi-use collector, ASAE Paper No. 81-4554, ASAE, St. Joseph, Michigan 49085.

16. Kreith, Frank and Jan F. Kreider. 1978. Principles of Solar Engineering. Hemisphere Publishing Corporation, Washington, D.C., 778 pp.

17. McFate, K. L. 1976. Optimizing solar energy modification of farrowing house environments, Proceedings of Symposium on use of Solar Energy for Livestock Production, November 9-10, Auburn, Alabama, pp. 153-160.

18. Meador, Neil F., Les Eggerman and Kenneth L. McFate. 1978. Solar heating of water for baby pig environmental control, Proceedings of the Conference on Solar Energy for Livestock Production, Novemver 28-29, College Park, Maryland, pp. 113-120.

19. National Science Foundation. 1976. Solar energy applications in agriculture-potential research needs and adoption strategies, Prepared for ARS-USDA, Agricultural Experiment Station, University of Maryland, College Park, 305 pp.

20. Ong, K. S. 1974. A finite difference method to evaluate the thermal performance of a solar water heater, Solar Energy 16:137-147.

21. Riley, William, Jr., Robert J. Moody, John P. McBride and Gills J. Favard. 1982. Performance monitoring results for domestic solar hot water heating systems constructed in the solar utilization, economic deployment and employment (SUEDE) program, Proceedings of 1982 Wind and Solar Energy Technology Conference, Columbia, Missouri, 457 pp.

22. Rode, Donald W. 1979. Portable, multipurpose solar collectors, Solar Grain Drying Proceedings, March 27-28, Ames, Iowa, pp. 87-94.

23. Shitzer, A., D. Kalmanoviz, Y. Zvirin and G. Grossman. 1978. Experiments with a flat plate solar water heating system in thermosyphonic flow, Solar Energy 22:27-35.

24. Smith C. C. 1978. Multipli use solar system for agriculture, Colorado State University, Fort Collins, Colorado 80523.

25. Spillman, C. K., F. V. Robbins and R. H. Hines. 1978. Solar Energy for reducing fossil fuel usage in farrowing houses, Proceedings of the Conference of Solar Energy for Livestock Production, November 28-29, College Park, Maryland, pp. 157-173.

26. Stipanuk, D. M., R. K. Koelsh and R. C. Roberg. 1979. Energy and economic analysis of heat recovery vs. solar water heating on dairy farms, ASAE Papar No. 79-3537, ASAE, St. Joseph, Michigan 49085.

27. Stout, B. A. and C. A. Myers. 1978. Agricultural applications of solar energy, Proceedings of the Annual Meeting of the American Section of the International Solar Energy Society, Inc:Soler Diversification, Denver. Colorado, August 28-31, 1978 Tutorials Volume, pp. 149-156.

28. Studman, C. J. 1979. Once-through solar water heater system for farm dairies, Journal of Agricultural Engineering Research 24:149-156.

29. Trotter, W. K., W. G. Heid, Jr. and R. G. McElroy. 1979. Solar Energy for agriculture:review of research, ESCS-67, National Economics Division, Economics,

Statistics and Cooperatives Service, USDA, Washington, D.C. 20250.

30. Wiersma, Frank and D. L. Larson. 1978. Solar heat recovery systems to heat water for dairies, Proceedings of the Conference of Solar Energy for Livestock Production, November 28-29, College Park, Maryland, pp. 187-196.

31. Vaughn, D. H., B. J. Holmes and E. S. Bell. 1980. Solar heating of a swine nursery, Transactions of the ASAE 23(1):150-156.

Appendix A

1981 AND 1982 TEST DATA

Data from the 1981 and 1982 tests are presented. The 1981 data are presented in Table A1. The 1982 data are presented in Table A2.

TABLE A1: 1981 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-W (%)
					18.3					
								0.6713	2.2312	30.1
07:21:10:30	37.4	27.0	18.7	32.6	19.5	80	446			
								0.6667	2.2057	30.2
07:21:11:00	40.9	28.0	18.4	34.3	20.7	87	446			
								1.0712	3.0690	34.9
07:21:11:30	43.4	29.0	18.8	35.8	22.6	91	446			
								0.9561	5.2320	18.3
07:21:12:00	48.1	30.3	18.9	38.0	24.3	99	446			
								1.5029	5.5306	27.2
07:21:12:30	63.2	33.2	18.5	43.8	26.9	127	446			
								1.7608	4.3954	40.2
07:21:13:00	53.2	32.0	19.1	40.4	30.0	106	446			
								1.3714	5.3525	25.6
07:21:13:30	50.8	32.2	19.6	40.1	32.4	97	446			
								1.5949	6.1785	25.8
07:21:14:00	65.2	36.4	22.1	46.5	35.3	127	446			
								1.6497	5.9167	27.9
07:21:14:30	67.8	40.9	27.5	50.0	38.2	128	446			
								1.3769	5.8396	23.6
07:21:15:00	64.8	42.6	31.7	50.5	40.6	126	446			

TABLE A1 (cont.): 1981 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					17.1					
								0.3662	2.2807	16.1
07:22:10:00	31.7	25.4	17.9	29.0	17.8	61	446			
								0.5785	3.3240	17.4
07:22:10:30	39.4	27.4	17.5	32.9	18.8	84	446			
								0.7483	4.0175	18.6
07:22:11:00	45.5	29.0	17.2	35.8	20.1	94	446			
								1.1329	4.8731	23.2
07:22:11:30	53.5	31.0	17.4	39.1	22.1	111	446			
								1.7257	5.5674	31.0
07:22:12:00	63.0	33.2	17.4	43.2	25.1	123	446			
								2.0326	5.7555	35.3
07:22:12:30	68.4	34.1	17.0	45.3	28.7	130	446			
								2.1002	6.3212	33.2
07:22:13:00	68.4	35.1	18.3	46.3	32.4	127	446			
								2.0081	6.7436	29.8
07:22:13:30	67.2	36.7	21.8	47.4	35.9	128	446			
								1.6007	6.4740	24.7
07:22:14:00	65.3	39.1	26.3	48.5	38.8	126	446			
								1.2574	5.6119	22.4
07:22:14:30	66.5	41.9	29.8	50.2	41.0	129	446			

TABLE A1 (cont.): 1981 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					17.9					
								0.2918	2.7200	10.7
07:23:09:30	35.1	26.1	18.1	30.7	18.4	76	446			
								0.8103	3.4208	23.7
07:23:10:00	38.4	27.3	18.2	32.6	19.8	83	446			
								0.7466	4.0794	18.3
07:23:10:30	44.1	28.4	17.2	34.7	21.1	96	446			
								1.1423	4.6160	24.7
07:23:11:00	51.3	31.1	18.6	38.8	23.1	107	446			
								1.4345	5.0279	29.5
07:23:11:30	56.6	32.1	18.4	41.0	25.8	116	446			
								1.7003	5.4475	31.2
07:23:12:00	63.1	33.5	18.6	43.7	28.8	126	446			
								1.9770	5.7226	34.5
07:23:12:30	68.3	34.9	18.9	46.1	32.2	131	446			
								2.1966	5.8755	37.4
07:23:13:00	72.1	37.5	22.4	49.2	36.1	138	446			
								1.9093	6.0449	31.6
07:23:13:30	75.0	41.6	28.7	52.5	39.5	150	446			
								1.6449	6.0826	27.0
07:23:14:00	69.5	43.0	32.2	52.7	42.4	139	446			
								1.4264	5.8965	24.2
07:23:14:30	75.7	46.6	35.4	56.1	44.9	150	446			

TABLE A1 (cont.): 1981 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kwh)	Ins (kwh)	Err-w (%)
					17.7					
								0.2309	0.7887	29.3
08:14:09:30	27.8	23.9	18.1	27.0	18.1	47	446			
								0.5674	0.7654	74.1
08:14:10:00	26.7	23.6	18.2	26.2	19.1	41	446			
								0.2034	1.7057	11.9
08:14:10:30	34.3	26.3	18.5	31.6	19.5	65	446			
								0.6727	2.2643	29.7
08:14:11:00	37.8	27.5	18.3	34.3	20.7	69	446			
								0.8600	1.9100	45.0
08:14:11:30	37.4	27.4	18.3	34.1	22.2	68	446			
								0.6740	1.8369	36.7
08:14:12:00	34.4	26.9	18.5	31.9	23.4	59	446			
								0.6594	1.9851	33.2
08:14:12:30	33.6	26.8	18.6	31.3	24.6	58	446			
								0.8608	3.5423	24.3
08:14:13:00	54.1	32.3	19.1	41.1	26.1	106	446			
								1.8129	5.6316	32.2
08:14:13:30	62.6	34.9	19.6	47.4	29.3	107	446			
								1.8603	6.0677	30.7
08:14:14:00	65.8	36.8	22.2	49.9	32.5	112	446			
								1.5466	4.7026	32.9
08:14:14:30	60.4	37.7	25.6	49.0	35.3	104	446			

1. Tank Elevation= vertical distance between tank outlet and collector outlet, m
2. Date-Time= month:day:hour(local standard time):minutes
3. Ta-i= temperature of air entering tne heat exchanger, C
4. Ta-o= temperature of air leaving the heat exchanger, C
5. Tw-i= temperature of water entering the heat exchanger, C
6. Tw-o= temperature of water leaving the heat exchanger, C
7. Ttank= average temperature of the water storage, C
8. Mwat= average water flow rate during 30 minute interval, kg/hr
9. Mair= air flow rate in the collector, kg/hr
10. Ener-tank= energy added to water storage during 30 minute interval, kWh
11. Ins= average insolation from measurements taken at the beginning and end of the 30 minute interval, kWh
12. Eff-W= Ener-tank/Ins for the 30 minute interval, %

TABLE A2: 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kwh)	Ins (kwh)	Eff-w (%)
					13.6					
								0.4140	2.7573	15.0
07:28:09:00	32.5	23.3	13.7	29.7	14.3	56	405			
								0.6885	3.8649	17.8
07:28:09:30	39.7	25.4	13.8	34.5	15.5	67	405			
								0.9638	4.5633	21.1
07:28:10:00	46.5	27.3	13.8	38.1	17.2	77	405			
								1.1419	5.0960	22.4
07:28:10:30	52.4	28.4	13.7	40.8	19.2	86	405			
								1.5287	5.6110	27.2
07:28:11:00	58.2	30.5	14.1	44.4	21.9	89	405			
								1.4782	5.6180	26.3
07:28:11:30	62.4	32.1	14.2	46.8	24.5	90	405			
								1.6782	6.1176	27.4
07:28:12:00	64.0	33.3	14.6	48.1	27.5	89	405			
								1.6131	5.9441	27.1
07:28:12:30	65.9	33.9	14.8	49.3	30.3	90	405			
								1.7273	5.7658	30.0
07:28:13:00	63.5	32.3	15.0	44.8	33.4	101	405			
								1.5879	5.9351	26.8
07:28:13:30	61.9	34.4	16.5	48.6	36.2	84	405			
								1.3487	6.0440	22.3
07:28:14:00	60.4	35.3	20.0	49.1	38.6	84	405			
								1.1897	5.5879	21.3
07:28:14:30	58.4	36.1	24.6	45.6	40.7	103	405			
								0.8775	4.8975	17.9
07:28:15:00	55.0	38.2	28.9	46.5	42.2	92	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Err-W (%)
					14.3					
								0.4344	2.8908	15.0
07:29:09:00	33.6	23.9	14.2	30.7	15.0	57	405			
								0.6308	3.5208	17.9
07:29:09:30	38.2	25.5	14.5	33.8	16.1	64	405			
								0.7225	3.5637	20.3
07:29:10:00	41.2	26.1	14.2	34.9	17.4	71	405			
								0.8342	4.1105	20.3
07:29:10:30	46.3	27.2	14.3	38.2	18.9	78	405			
								1.1586	5.2871	21.9
07:29:11:00	53.6	29.6	14.7	41.9	20.9	86	405			
								1.3314	5.4587	24.4
07:29:11:30	57.0	30.7	14.6	43.6	23.3	88	405			
								1.3863	5.8569	23.7
07:29:12:00	60.7	32.0	14.7	46.0	25.7	89	405			
								1.5145	6.0290	25.1
07:29:12:30	62.7	32.9	15.1	47.4	28.4	90	405			
								1.5534	6.1134	25.4
07:29:13:00	63.3	33.2	15.4	47.9	31.1	90	405			
								1.4580	5.8720	24.8
07:29:13:30	61.9	33.5	16.0	48.0	33.7	86	405			
								1.2746	5.4606	23.3
07:29:14:00	58.9	33.9	18.1	47.3	35.9	83	405			
								1.1149	5.0711	22.0
07:29:14:30	57.8	35.8	21.9	47.9	37.9	82	405			
								0.7466	3.3351	22.4
07:29:15:00	50.5	36.0	25.4	45.1	39.2	71	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-W (%)
					13.2					
								0.4544	3.2366	14.0
07:30:09:00	33.6	23.2	13.6	30.2	14.0	61	405			
								0.6549	3.5269	18.6
07:30:09:30	38.9	25.0	13.7	33.9	15.1	67	405			
								0.8608	3.9796	21.6
07:30:10:00	43.1	25.9	13.7	35.3	16.7	77	405			
								0.9075	4.1650	21.8
07:30:10:30	47.8	27.3	13.7	38.4	18.3	80	405			
								1.2947	5.5158	23.5
07:30:11:00	54.9	29.4	13.9	41.7	20.5	89	405			
								1.3130	5.0578	26.0
07:30:11:30	55.6	29.5	14.1	42.1	22.8	90	405			
								1.4100	5.4[illegible]63	25.8
07:30:12:00	55.9	30.3	14.5	43.1	25.3	87	405			
								1.3638	5.6285	24.2
07:30:12:30	60.1	30.1	14.4	42.6	27.7	103	405			
								1.3412	5.4048	24.8
07:30:13:00	62.7	32.1	14.5	47.1	30.1	91	405			
								1.4138	5.1682	27.4
07:30:13:30	60.5	31.9	15.0	46.0	32.6	90	405			
								1.2977	4.6554	27.9
07:30:14:00	55.7	32.0	16.1	44.9	34.9	80	405			
								1.1111	5.1065	21.8
07:30:14:30	57.7	33.9	19.1	46.5	36.8	84	405			
								1.0420	5.0233	20.7
07:30:15:00	58.3	36.5	23.8	48.0	38.7	88	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					14.5					
								0.5567	3.3590	16.6
08:02:09:00	37.2	25.0	14.6	32.8	15.5	65	405			
								0.7398	3.9525	18.7
08:02:09:30	42.6	26.5	14.6	36.0	16.8	73	405			
								1.0240	4.4849	22.8
08:02:10:00	48.2	27.9	14.4	38.7	18.6	81	405			
								1.2432	5.2011	24.0
08:02:10:30	53.9	29.4	14.6	41.9	20.8	87	405			
								1.2938	5.6134	23.0
08:02:11:00	56.5	29.5	14.6	41.2	23.1	99	405			
								1.3154	5.9544	22.1
08:02:11:30	55.9	30.7	14.9	44.0	25.4	84	405			
								1.2716	6.1450	20.7
08:02:12:00	54.4	30.4	15.0	43.6	27.6	82	405			
								1.2186	6.2939	19.3
08:02:12:30	54.1	30.5	15.4	43.9	29.8	80	405			
								1.3134	6.2505	21.0
08:02:13:00	60.0	32.3	15.7	46.9	32.1	86	405			
								1.4353	6.2137	23.1
08:02:13:30	61.9	33.4	16.7	47.9	34.6	89	405			
								1.4196	5.9132	24.0
08:02:14:00	63.0	35.4	19.9	49.6	37.1	90	405			
								1.1811	5.5775	21.2
08:02:14:30	62.0	37.4	24.7	48.8	39.2	99	405			
								0.9932	5.2323	19.0
08:02:15:00	61.6	40.4	29.4	51.1	40.9	95	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					14.4					
								0.5613	2.0253	27.7
08:03:09:00	32.9	24.2	14.5	30.3	15.4	53	405			
								0.4460	0.7300	61.1
08:03:09:30	29.5	23.2	14.8	28.2	16.2	45	405			
								0.2599	0.5075	51.2
08:03:10:00	27.3	22.4	14.7	26.4	16.6	41	405			
								0.2046	0.4400	46.5
08:03:10:30	25.6	21.8	14.6	25.2	17.0	35	405			
								0.1646	0.2778	59.2
08:03:11:00	24.2	21.3	14.7	24.1	17.3	30	405			
								0.1272	0.1385	91.8
08:03:11:30	23.2	20.9	14.7	23.2	17.5	27	405			
								0.1204	0.2062	58.4
08:03:12:00	22.9	20.7	14.7	22.9	17.7	26	405			
								0.0691	0.2003	34.5
08:03:12:30	22.4	20.4	14.7	22.4	17.8	26	405			
								0.0935	0.2963	31.5
08:03:13:00	22.6	20.6	14.8	22.5	18.0	25	405			
								0.1389	0.3927	35.4
08:03:13:30	23.0	20.9	14.9	23.0	18.3	24	405			
								0.0880	0.3407	25.8
08:03:14:00	22.5	20.7	14.9	22.5	18.4	24	405			
								0.0876	0.8179	10.7
08:03:14:30	24.3	21.7	15.0	23.9	18.6	29	405			
								0.1731	1.0429	16.6
08:03:15:00	26.0	22.6	15.1	25.7	18.9	32	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kwh)	Ins (kwh)	Eff-w (%)
					13.2					
								0.6403	3.2340	19.8
08:04:09:00	36.9	25.7	14.0	32.9	14.3	57	405			
								0.8306	3.9409	21.1
08:04:09:30	41.9	27.4	14.0	36.5	15.8	63	405			
								0.9895	4.3470	22.8
08:04:10:00	46.8	28.8	14.0	39.4	17.5	69	405			
								1.2713	4.8739	26.1
08:04:10:30	51.5	29.5	14.1	41.7	19.8	77	405			
								1.2378	4.6946	26.4
08:04:11:00	54.2	30.6	14.3	44.0	21.9	77	405			
								1.4377	5.6103	25.6
08:04:11:30	59.9	31.2	14.2	44.0	24.5	94	405			
								1.6150	5.9006	27.4
08:04:12:00	62.6	33.7	14.7	43.3	27.3	84	405			
								1.5971	5.6921	28.1
08:04:12:30	62.6	34.4	15.3	49.4	30.1	80	405			
								1.7022	6.0161	28.3
08:04:13:00	62.2	34.2	15.1	48.5	33.1	81	405			
								1.5090	5.6572	26.7
08:04:13:30	61.3	33.7	15.9	47.9	35.8	84	405			
								1.3526	4.9822	27.1
08:04:14:00	59.5	35.3	18.7	48.7	38.2	78	405			
								1.2512	5.1434	24.3
08:04:14:30	60.8	37.9	23.9	49.7	40.4	86	405			
								1.0036	4.8934	20.5
08:04:15:00	61.9	41.5	29.2	52.3	42.2	86	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					14.6					
								0.7366	3.0545	24.1
08:05:09:00	37.3	25.9	14.8	33.1	15.9	60	405			
								0.7583	3.3732	22.5
08:05:09:30	40.7	26.6	14.8	34.9	17.3	68	405			
								0.9763	4.7191	20.7
08:05:10:00	48.2	28.8	14.8	39.4	19.0	77	405			
								1.1824	4.6730	25.3
08:05:10:30	52.4	30.0	15.3	41.8	21.1	82	405			
								1.3565	5.1703	26.2
08:05:11:00	58.0	31.8	15.2	45.6	23.5	84	405			
								1.6003	5.6816	28.2
08:05:11:30	62.5	32.7	15.5	46.9	26.3	92	405			
								1.7174	6.2084	27.7
08:05:12:00	66.6	34.8	15.8	50.2	29.3	90	405			
								1.7902	6.2491	28.6
08:05:12:30	66.8	35.2	16.2	50.5	32.5	89	405			
								1.7218	6.2620	27.5
08:05:13:00	66.0	35.9	16.8	51.2	35.5	85	405			
								1.6332	6.3498	25.7
08:05:13:30	67.4	36.4	18.5	51.4	38.4	92	405			
								1.5123	5.8469	25.9
08:05:14:00	66.8	38.9	23.1	52.6	41.0	92	405			
								1.2816	5.3713	23.9
08:05:14:30	65.7	41.9	28.6	54.1	43.3	91	405			
								0.9166	4.7444	19.3
08:05:15:00	62.6	43.3	32.5	53.5	44.9	90	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					15.0					
								0.4219	2.3109	18.3
08:06:09:00	33.0	24.4	15.0	30.5	15.7	53	405			
								0.5975	3.4491	17.3
08:06:09:30	38.5	26.4	15.1	34.3	16.8	61	405			
								0.8530	4.1814	20.4
08:06:10:00	44.7	28.1	15.3	37.6	18.3	72	405			
								0.9631	4.2068	22.9
08:06:10:30	46.1	28.5	15.1	38.2	20.0	74	405			
								1.0137	4.1375	24.5
08:06:11:00	49.0	29.6	15.4	40.8	21.8	74	405			
								1.1222	4.5850	24.5
08:06:11:30	51.8	30.6	15.7	42.5	23.8	77	405			
								1.1470	4.9581	23.1
08:06:12:00	54.5	31.2	15.7	43.8	25.8	81	405			
								1.3368	5.2359	25.5
08:06:12:30	58.2	32.1	15.9	45.7	28.1	85	405			
								1.4194	6.0223	23.6
08:06:13:00	62.6	33.8	16.2	48.5	30.6	87	405			
								1.6130	6.0601	26.6
08:06:13:30	61.4	34.1	16.7	48.2	33.5	84	405			
								1.3677	5.8109	23.5
08:06:14:00	61.8	35.0	18.4	49.3	35.9	84	405			
								1.3127	5.4083	24.3
08:06:14:30	61.3	37.0	22.4	49.7	38.2	87	405			
								1.0818	4.9691	21.8
08:06:15:00	60.5	39.2	26.6	50.5	40.1	86	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Err-w (%)
					13.5					
								0.5270	3.4000	15.5
08:07:09:00	35.4	24.6	14.0	32.0	14.4	59	405			
								0.7703	4.0500	19.0
08:07:09:30	41.1	26.2	14.0	36.0	15.8	66	405			
								0.9325	4.6500	20.1
08:07:10:00	47.4	27.2	14.0	37.0	17.4	85	405			
								1.2568	5.1000	24.6
08:07:10:30	52.7	29.0	14.0	41.0	19.6	85	405			
								1.5000	5.5500	27.0
08:07:11:00	58.1	30.4	14.0	44.0	22.3	90	405			
								1.5000	5.9500	25.2
08:07:11:30	62.2	31.9	15.0	47.0	24.9	92	405			
								1.7838	5.7000	31.3
08:07:12:00	62.3	31.2	15.0	45.0	28.1	101	405			
								1.5406	6.0000	25.7
08:07:12:30	65.2	33.2	15.0	49.0	30.8	91	405			
								1.6622	6.3000	26.4
08:07:13:00	66.7	34.3	15.0	50.0	33.7	90	405			
								1.7433	6.1500	28.3
08:07:13:30	65.9	35.1	17.0	50.0	36.3	91	405			
								1.5000	5.8000	25.9
08:07:14:00	64.9	36.9	21.0	51.0	39.4	91	405			
								1.2564	5.3554	23.5
08:07:14:30	63.5	39.5	26.4	51.8	41.6	92	405			
								0.9045	4.6963	19.3
08:07:15:00	61.7	41.6	30.8	52.1	43.2	92	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					15.7					
								0.3932	3.4598	11.4
08:08:09:00	33.8	24.8	15.9	31.4	16.4	57	405			
								0.5473	4.1620	13.1
08:08:09:30	39.1	26.1	16.0	34.4	17.4	69	405			
								0.7941	4.7944	16.6
08:08:10:00	46.0	28.4	16.2	37.9	18.8	79	405			
								1.0636	5.3152	20.0
08:08:10:30	52.1	29.8	16.4	41.2	20.7	87	405			
								1.2652	5.7526	22.0
08:08:11:00	57.9	31.1	16.5	43.5	22.9	97	405			
								1.4379	6.0833	23.6
08:08:11:30	61.8	32.7	16.8	46.1	25.4	97	405			
								1.5802	6.2697	25.2
08:08:12:00	63.7	33.4	16.9	47.5	28.2	96	405			
								1.5573	6.3664	24.5
08:08:12:30	65.8	33.9	16.9	49.0	30.9	97	405			
								1.6298	6.3693	25.6
08:08:13:00	64.6	32.9	17.0	45.8	33.8	107	405			
								1.5497	6.3074	24.6
08:08:13:30	63.9	33.5	18.4	47.9	36.5	100	405			
								1.3351	5.9968	22.3
08:08:14:00	63.5	36.9	22.2	50.7	38.9	91	405			
								1.1056	5.5906	19.8
08:08:14:30	62.1	39.3	26.6	51.1	40.8	90	405			
								0.9150	5.0766	18.0
08:08:15:00	59.7	41.0	30.5	51.0	42.5	89	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation = 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					11.7					
								0.4682	3.4311	13.4
08:10:09:00	32.4	22.6	12.2	29.8	12.5	54	405			
								0.7864	4.7254	16.6
08:10:09:30	39.9	24.6	12.3	34.4	13.9	67	405			
								1.0614	5.0394	21.1
08:10:10:00	45.4	26.2	12.2	36.9	15.8	75	405			
								1.1496	5.1772	22.2
08:10:10:30	49.9	27.1	12.3	39.6	17.8	81	405			
								1.4914	6.1649	24.2
08:10:11:00	56.2	29.1	12.5	42.6	20.4	87	405			
								1.4470	5.9529	24.3
08:10:11:30	58.3	29.4	12.7	43.2	23.0	92	405			
								1.6897	6.1955	27.3
08:10:12:00	57.6	29.9	12.7	43.7	25.9	87	405			
								1.4203	5.6773	25.0
08:10:12:30	53.4	30.6	12.9	45.7	28.4	82	405			
								1.6077	6.3411	25.4
08:10:13:00	60.7	29.7	13.2	42.4	31.3	103	405			
								1.5799	6.4432	24.5
08:10:13:30	60.9	32.1	14.0	47.3	34.1	84	405			
								1.5521	6.2519	24.8
08:10:14:00	62.3	33.8	16.3	48.6	36.8	87	405			
								1.2234	5.0960	24.1
08:10:14:30	59.6	35.5	22.0	48.4	39.0	89	405			
								1.0902	5.4130	20.1
08:10:15:00	60.0	39.2	27.8	50.0	40.9	91	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					12.5					
								0.4190	3.4934	12.0
08:11:09:00	31.7	22.3	12.7	29.1	13.2	56	405			
								0.6843	4.3191	15.8
08:11:09:30	37.5	24.2	13.1	33.1	14.4	64	405			
								0.8358	4.2925	19.5
08:11:10:00	42.6	25.7	13.2	35.7	15.9	73	405			
								1.0118	5.5107	18.4
08:11:10:30	48.0	27.0	12.8	38.6	17.7	79	405			
								1.1356	5.5151	21.5
08:11:11:00	52.2	27.8	13.0	40.5	19.8	86	405			
								1.4120	6.2130	22.7
08:11:11:30	54.0	29.0	13.3	41.8	22.3	85	405			
								1.3303	6.3203	21.0
08:11:12:00	53.2	28.4	13.2	41.2	24.6	86	405			
								1.2968	6.6349	19.4
08:11:12:30	53.8	29.0	13.4	42.5	26.9	83	405			
								1.3012	6.5853	19.8
08:11:13:00	53.7	29.5	13.8	42.8	29.2	81	405			
								1.2753	6.5095	19.6
08:11:13:30	58.5	30.8	14.1	45.0	31.4	87	405			
								1.3104	6.0110	21.8
08:11:14:00	58.7	32.2	15.9	46.4	33.7	84	405			
								1.2959	5.6415	23.0
08:11:14:30	58.1	34.4	20.0	47.3	36.0	85	405			
								0.9935	5.2072	19.1
08:11:15:00	56.4	36.7	24.8	47.7	37.8	84	405			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					12.6					
								0.1406	1.0996	12.8
08:12:09:00	24.3	18.9	12.8	22.9	12.9	36	281			
								0.2072	1.2953	15.9
08:12:09:30	25.5	19.4	12.8	23.8	13.2	38	281			
								0.2353	1.0096	23.4
08:12:10:00	25.5	19.6	12.9	23.9	13.7	37	281			
								0.1871	1.0075	18.6
08:12:10:30	25.4	19.6	12.9	23.9	14.0	36	281			
								0.1974	0.8007	24.7
08:12:11:00	24.5	19.4	13.0	23.3	14.3	33	281			
								0.1769	1.0139	17.4
08:12:11:30	24.8	19.6	13.0	23.6	14.7	33	281			
								0.1951	1.3698	14.2
08:12:12:00	26.2	19.9	13.0	24.6	15.0	37	281			
								0.2363	1.0469	22.6
08:12:12:30	26.0	19.8	13.0	24.4	15.4	37	281			
								0.1721	0.4619	37.3
08:12:13:00	24.1	19.4	13.2	23.1	15.7	32	281			
								0.1494	0.7460	20.0
08:12:13:30	24.4	19.7	13.2	23.4	16.0	31	281			
								0.1403	0.5139	27.1
08:12:14:00	23.7	19.5	13.3	23.0	16.2	29	281			
								0.1608	0.6327	25.4
08:12:14:30	23.9	19.7	13.4	23.2	16.5	29	281			
								0.1678	0.7097	23.6
08:12:15:00	24.5	20.0	13.5	23.6	16.3	31	281			

TABLE A2 (Conc.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Effi-w (%)
					19.0					
								0.0965	0.9640	10.0
08:13:09:00	25.7	21.4	15.3	24.8	19.2	30	281			
								0.1891	1.5550	12.2
08:13:09:30	29.1	22.5	15.6	27.2	19.5	38	281			
								0.2792	2.6023	10.7
08:13:10:00	33.1	23.9	16.1	29.7	20.0	46	281			
								0.3125	2.2342	13.7
08:13:10:30	33.7	24.3	16.9	30.1	20.5	48	281			
								0.4432	3.7864	11.7
08:13:11:00	37.6	25.9	17.9	32.6	21.3	54	281			
								0.4380	3.9703	11.0
08:13:11:30	39.2	26.3	18.7	33.0	22.1	61	281			
								0.4575	4.3061	10.6
08:13:12:00	39.6	27.2	19.6	34.1	22.9	57	281			
								0.5318	7.2777	7.3
08:13:12:30	43.3	28.4	20.1	35.9	23.8	64	281			
								0.5900	6.5739	9.0
08:13:13:00	44.9	29.2	20.5	37.2	24.9	63	281			
								0.5730	5.9576	9.6
08:13:13:30	46.0	29.5	20.7	37.6	25.9	66	281			
								0.6693	6.2046	10.8
08:13:14:00	47.3	29.8	20.9	38.7	27.1	67	281			
								0.6413	5.9269	10.8
08:13:14:30	48.3	29.7	21.0	38.2	28.2	73	281			
								0.6582	5.5000	11.9
08:13:15:00	49.7	30.7	21.0	40.0	29.4	67	281			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (Kg/hr)	Mair (Kg/hr)	Ener-tank (Kwh)	Ins (Kwh)	Eff-W (%)
					13.0					
								0.3973	1.6112	24.7
08:16:09:00	30.6	21.3	13.8	26.8	13.7	48	281			
								0.3612	2.7586	13.1
08:16:09:30	34.6	22.3	13.8	29.2	14.4	54	281			
								0.6527	4.6191	14.1
08:16:10:00	44.6	24.7	14.0	34.1	15.5	67	281			
								0.8941	4.5290	19.7
08:16:10:30	48.5	25.7	14.1	36.1	17.1	70	281			
								0.9902	5.5296	17.9
08:16:11:00	55.4	27.0	14.3	39.3	18.8	77	281			
								1.2450	5.7474	21.7
08:16:11:30	59.6	28.0	14.2	40.4	21.0	81	281			
								1.1537	5.5322	20.9
08:16:12:00	61.4	28.2	14.3	41.4	23.1	82	281			
								1.3370	5.8168	23.0
08:16:12:30	63.7	29.1	14.6	42.8	25.4	82	281			
								1.3355	6.1287	21.8
08:16:13:00	65.2	29.6	14.8	43.8	27.8	83	281			
								1.2500	5.3060	23.6
08:16:13:30	62.4	29.1	14.9	43.1	30.0	80	281			
								1.1587	5.3715	21.6
08:16:14:00	60.1	29.3	15.2	42.6	32.1	78	281			
								1.1497	5.8057	19.8
08:16:14:30	62.0	30.1	16.5	43.5	34.1	83	281			
								1.0059	4.7594	21.1
08:16:15:00	57.9	30.5	19.3	42.0	35.3	81	281			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.3 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					13.7					
								0.4526	3.1017	14.6
08:17:09:00	35.5	22.5	14.1	29.6	14.5	56	281			
								0.6105	3.6074	16.9
08:17:09:30	39.1	23.6	14.3	32.0	15.5	59	281			
								0.6443	4.3900	14.7
08:17:10:00	43.1	24.4	14.3	33.8	16.7	65	281			
								0.7286	3.4895	20.9
08:17:10:30	43.4	24.5	14.4	33.8	17.9	66	281			
								0.6620	3.5154	18.8
08:17:11:00	43.4	24.3	14.3	33.9	19.1	65	281			
								0.7503	3.5921	20.9
08:17:11:30	44.6	24.9	14.4	34.6	20.4	66	281			
								0.6858	3.2128	21.3
08:17:12:00	46.1	25.1	14.7	35.6	21.6	68	281			
								0.7357	3.9171	18.8
08:17:12:30	48.0	25.8	14.9	36.5	22.9	69	281			
								0.9755	5.9608	16.4
08:17:13:00	57.5	27.6	14.8	40.5	24.7	78	281			
								1.1431	6.2920	18.2
08:17:13:30	61.3	28.7	15.0	41.8	26.7	82	281			
								1.2319	5.6870	21.7
08:17:14:00	61.1	29.1	15.3	42.6	28.8	79	281			
								1.1349	5.6529	20.1
08:17:14:30	59.9	29.1	15.8	42.4	30.8	78	281			
								1.0284	5.0437	20.4
08:17:15:00	56.3	30.0	17.8	42.5	32.7	77	281			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.6 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kwh)	Ins (kwh)	Err-w (%)
					13.5					
								0.6292	2.1127	29.8
08:18:09:00	34.2	24.4	13.9	31.0	14.6	70	504			
								0.6580	3.2272	20.4
08:18:09:30	36.8	25.6	14.0	33.1	15.8	71	504			
								0.7692	3.3853	22.7
08:18:10:00	38.7	26.4	14.2	34.3	17.1	74	504			
								0.9581	3.4102	28.1
08:18:10:30	38.1	26.3	14.2	34.0	18.8	72	504			
								0.6063	1.9151	31.7
08:18:11:00	35.4	25.6	14.1	32.6	19.9	64	504			
								0.6932	2.9002	23.9
08:18:11:30	37.9	26.6	14.5	34.5	21.1	68	504			
								0.8847	4.1586	21.3
08:18:12:00	43.0	28.1	14.6	37.5	22.7	79	504			
								0.7443	1.8178	40.9
08:18:12:30	36.7	26.4	14.4	33.9	24.0	64	504			
								0.5309	1.5424	34.4
08:18:13:00	34.3	25.9	14.6	32.6	24.9	57	504			
								0.4649	1.3457	34.5
08:18:13:30	33.4	25.9	14.8	32.1	25.7	53	504			
								0.4924	2.2677	21.7
08:18:14:00	34.9	26.5	15.1	33.3	26.6	57	504			
								0.6480	2.7329	23.7
08:18:14:30	37.1	27.2	15.5	34.7	27.7	62	504			
								0.6119	2.1167	28.9
08:18:15:00	36.0	27.4	16.1	34.4	28.8	57	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.6 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					15.8					
								-0.4186	1.4613	-28.6
08:19:09:00	35.5	25.3	13.9	32.4	15.0	67	504			
								0.7972	3.7700	21.1
08:19:09:30	39.8	26.8	14.1	35.0	16.4	75	504			
								1.0387	4.4347	23.4
08:19:10:00	45.2	28.0	14.0	37.6	18.3	88	504			
								1.2401	4.9734	24.9
08:19:10:30	50.7	29.6	14.2	41.3	20.4	94	504			
								1.5276	5.4486	28.0
08:19:11:00	56.4	31.2	14.4	44.4	23.1	102	504			
								1.7563	5.7860	30.4
08:19:11:30	60.7	32.7	15.0	46.7	26.2	107	504			
								1.8417	5.9754	30.8
08:19:12:00	62.8	33.1	15.2	47.7	29.5	110	504			
								1.9207	6.0359	31.8
08:19:12:30	64.5	34.3	15.7	49.0	32.9	110	504			
								1.8416	5.9605	30.9
08:19:13:00	63.4	34.9	17.0	49.3	36.1	107	504			
								1.6127	5.7614	28.0
08:19:13:30	61.0	36.8	21.6	49.3	38.9	105	504			
								1.2913	5.5211	23.4
08:19:14:00	62.5	40.4	27.5	51.9	41.2	110	504			
								1.1530	4.3841	26.3
08:19:14:30	59.0	42.4	32.1	51.6	43.2	103	504			
								0.4819	0.6018	80.1
08:19:15:00	46.8	40.0	34.3	45.6	44.1	72	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.6 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Err-w (%)
					13.0					
								0.6016	1.0077	59.7
08:20:09:00	33.6	23.9	13.6	31.0	14.1	67	504			
								0.8128	4.0149	20.2
08:20:09:30	39.3	26.0	14.1	34.7	15.5	78	504			
								1.0179	4.7034	21.6
08:20:10:00	46.4	28.2	13.9	38.4	17.3	89	504			
								1.3352	5.2340	25.5
08:20:10:30	52.5	30.0	14.0	42.5	19.7	96	504			
								1.5829	5.6521	28.0
08:20:11:00	57.8	31.3	14.1	45.3	22.5	103	504			
								1.8232	6.0088	30.3
08:20:11:30	62.3	32.3	14.4	46.7	25.7	112	504			
								1.9609	6.2250	31.5
08:20:12:00	64.8	33.5	14.7	48.8	29.1	111	504			
								1.9781	6.3534	31.1
08:20:12:30	66.8	34.8	15.1	50.5	32.6	109	504			
								2.0166	6.3480	31.8
08:20:13:00	67.2	34.2	16.1	48.6	36.2	123	504			
								1.8412	6.3161	29.2
08:20:13:30	66.2	37.5	21.4	51.7	39.4	114	504			
								1.4905	6.0341	24.7
08:20:14:00	66.5	41.3	27.7	54.1	42.0	115	504			
								1.2199	5.5810	21.9
08:20:14:30	65.9	44.5	33.0	55.4	44.2	115	504			
								0.9734	5.1062	19.1
08:20:15:00	64.7	46.7	36.8	56.3	45.9	112	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.6 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					14.0					
								0.5730	1.1453	50.0
08:23:09:00	33.2	24.0	14.1	30.9	15.0	66	504			
								0.7533	4.2118	17.9
08:23:09:30	39.3	25.9	14.3	34.1	16.3	82	504			
								1.0399	4.6800	22.2
08:23:10:00	46.0	28.3	14.4	38.3	18.2	90	504			
								1.3052	5.1729	25.2
08:23:10:30	51.7	30.0	14.5	41.3	20.5	98	504			
								1.4877	5.6237	26.5
08:23:11:00	57.8	31.7	14.5	45.0	23.1	104	504			
								1.7743	5.9793	29.7
08:23:11:30	62.6	33.4	14.8	47.4	26.2	108	504			
								1.8921	6.1012	31.0
08:23:12:00	64.1	34.0	15.1	48.6	29.6	109	504			
								1.9411	6.3894	30.4
08:23:12:30	66.1	34.8	15.3	49.7	33.0	110	504			
								1.9413	5.6056	34.6
08:23:13:00	60.0	34.3	16.4	47.5	36.4	100	504			
								1.5038	6.2597	24.0
08:23:13:30	62.7	35.7	20.6	47.2	39.0	123	504			
								1.4349	6.2664	22.9
08:23:14:00	65.0	40.2	26.8	51.7	41.6	120	504			
								1.0946	3.9693	27.6
08:23:14:30	57.3	41.9	31.6	50.9	43.5	96	504			
								0.5517	3.7943	14.5
08:23:15:00	57.4	43.6	34.8	52.0	44.5	97	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.6 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					14.4					
								0.4613	1.1404	42.2
08:25:09:00	32.3	24.3	14.6	30.3	15.2	62	504			
								0.7021	3.9306	17.9
08:25:09:30	38.0	26.3	14.8	34.3	16.4	73	504			
								0.9431	4.8020	19.6
08:25:10:00	44.7	28.3	14.6	37.7	18.1	85	504			
								1.1687	5.3314	21.9
08:25:10:30	50.3	29.9	14.7	40.9	20.2	94	504			
								1.4429	5.7963	24.9
08:25:11:00	56.0	31.3	14.9	44.0	22.7	103	504			
								1.6302	6.1556	26.5
08:25:11:30	59.9	32.4	15.1	45.3	25.6	110	504			
								1.7304	6.4232	26.9
08:25:12:00	62.0	32.9	15.2	46.5	28.6	112	504			
								1.7853	6.4730	27.6
08:25:12:30	63.1	33.6	15.5	47.4	31.8	112	504			
								1.7274	6.5481	26.4
08:25:13:00	62.6	33.9	16.2	47.9	34.8	109	504			
								1.5800	6.5112	24.3
08:25:13:30	61.3	35.8	19.4	49.3	37.6	103	504			
								1.2739	5.8154	21.9
08:25:14:00	59.5	38.0	25.1	49.8	39.8	105	504			
								0.9861	5.5130	17.5
08:25:14:30	59.0	41.2	30.0	51.3	41.5	102	504			
								0.6526	4.2721	15.3
08:25:15:00	54.5	42.0	33.6	49.9	42.7	92	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.6 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					13.6					
								0.4849	1.2604	38.5
08:26:09:00	32.1	23.4	13.6	29.8	14.4	64	504			
								0.7116	3.7542	19.0
08:26:09:30	37.7	25.8	13.8	33.9	15.7	72	504			
								0.8697	4.6547	18.7
08:26:10:00	44.1	27.9	13.9	37.4	17.2	83	504			
								1.2207	5.1824	23.6
08:26:10:30	50.1	29.6	14.0	41.0	19.4	92	504			
								1.4237	5.6371	25.3
08:26:11:00	56.1	31.0	14.3	43.9	21.9	102	504			
								1.6406	5.9768	27.4
08:26:11:30	60.6	32.6	14.6	46.3	24.8	107	504			
								1.8223	6.2010	29.4
08:26:12:00	62.7	33.2	14.8	47.6	28.0	109	504			
								1.8244	6.3099	28.9
08:26:12:30	64.2	33.9	15.0	48.6	31.2	109	504			
								1.8577	6.3061	29.5
08:26:13:00	63.7	34.5	16.0	49.1	34.5	106	504			
								1.6677	6.3310	26.3
08:26:13:30	63.1	35.6	19.2	49.3	37.4	111	504			
								1.2241	3.9743	30.8
08:26:14:00	53.9	36.8	24.2	47.1	39.6	90	504			
								0.9173	4.2865	21.4
08:26:14:30	53.7	39.2	28.7	48.0	41.2	91	504			
								0.6097	3.9368	15.5
08:26:15:00	53.4	40.4	32.0	48.1	42.3	97	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.6 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					11.8					
								0.3472	1.4345	24.2
08:27:09:00	29.5	21.9	11.9	29.1	12.4	54	504			
								0.6763	3.9247	17.2
08:27:09:30	36.0	24.1	11.9	32.6	13.6	69	504			
								0.9560	4.9062	19.5
08:27:10:00	43.3	26.5	12.1	36.6	15.3	83	504			
								1.2158	5.4305	22.4
08:27:10:30	50.1	28.5	12.2	40.6	17.4	92	504			
								1.5872	5.8647	27.1
08:27:11:00	56.2	30.2	12.6	43.6	20.2	101	504			
								1.7738	6.2004	28.6
08:27:11:30	60.8	31.8	12.9	46.0	23.3	106	504			
								1.8547	6.4093	28.9
08:27:12:00	62.3	31.9	13.0	46.9	26.6	108	504			
								1.9662	6.4838	30.3
08:27:12:30	63.9	32.0	13.2	46.4	30.0	116	504			
								1.9161	6.4736	29.6
08:27:13:00	63.2	32.2	13.5	47.0	33.4	112	504			
								1.7907	6.3460	28.2
08:27:13:30	62.3	34.2	15.9	49.1	36.6	102	504			
								1.5105	6.0640	24.9
08:27:14:00	61.2	36.6	21.4	49.8	39.2	105	504			
								1.2080	5.6861	21.2
08:27:14:30	60.2	39.8	27.9	50.8	41.4	107	504			
								0.9373	5.2288	17.9
08:27:15:00	59.2	41.9	32.8	50.4	43.0	119	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.9 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					11.8					
								0.5265	1.1484	45.8
08:30:09:00	30.7	21.9	11.7	28.5	12.7	63	504			
								0.8234	2.3262	35.4
08:30:09:30	36.3	24.1	12.0	32.3	14.2	73	504			
								0.9906	4.8639	20.4
08:30:10:00	42.5	26.7	12.1	36.8	15.9	78	504			
								1.1315	3.6227	31.2
08:30:10:30	44.4	26.7	12.2	37.1	17.9	86	504			
								0.8716	2.4396	35.7
08:30:11:00	37.2	25.4	12.2	34.0	19.4	66	504			
								0.5503	1.2284	44.8
08:30:11:30	30.8	23.4	12.1	30.0	20.4	50	504			
								0.4403	1.2640	34.8
08:30:12:00	29.5	23.2	12.4	29.1	21.2	45	504			
								0.2405	1.0584	22.7
08:30:12:30	28.5	23.0	12.6	28.1	21.6	43	504			
								0.2899	1.4288	20.3
08:30:13:00	29.0	22.4	12.3	28.0	22.1	50	504			
								0.3890	1.3413	29.0
08:30:13:30	28.8	23.2	12.7	28.5	22.8	43	504			
								0.3881	1.7859	21.7
08:30:14:00	30.2	23.9	12.7	29.7	23.5	45	504			
								0.2971	1.0106	29.4
08:30:14:30	28.3	23.2	12.9	28.2	24.0	40	504			
								0.2329	0.5685	41.0
08:30:15:00	26.2	22.4	13.5	26.3	24.4	35	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.9 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					13.1					
								0.3489	0.8905	39.2
08:31:09:00	24.7	20.8	12.8	24.4	13.8	41	504			
								0.2924	1.3201	22.2
08:31:09:30	26.9	21.9	12.8	26.1	14.3	45	504			
								0.4780	2.2514	21.2
08:31:10:00	32.5	24.7	13.2	30.4	15.1	54	504			
								0.6474	2.7545	23.5
08:31:10:30	34.6	25.4	13.3	32.4	16.3	58	504			
								1.2381	5.5082	22.5
08:31:11:00	47.9	29.3	13.3	40.1	18.4	84	504			
								1.6309	6.1236	26.6
08:31:11:30	54.8	30.5	13.5	42.9	21.3	100	504			
								1.7931	6.4824	27.7
08:31:12:00	57.7	31.5	13.6	44.3	24.5	103	504			
								1.7666	6.1907	28.5
08:31:12:30	58.5	32.4	13.8	45.9	27.6	98	504			
								1.7674	5.4341	32.5
08:31:13:00	52.2	31.4	14.0	42.8	30.7	87	504			
								1.2978	4.4467	29.2
08:31:13:30	49.1	31.1	15.5	42.3	33.0	81	504			
								1.2663	6.1458	20.6
08:31:14:00	54.9	33.8	18.7	46.0	35.2	93	504			
								1.2872	5.6678	22.7
08:31:14:30	54.4	35.4	22.7	45.6	37.5	100	504			
								0.9682	4.2369	22.9
08:31:15:00	51.1	37.4	26.6	45.9	39.2	86	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.9 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					13.2					
								0.4751	0.7808	60.9
09:01:09:00	30.5	22.7	13.3	28.9	14.0	60	504			
								0.6957	2.2129	31.4
09:01:09:30	36.1	24.5	13.3	31.8	15.2	76	504			
								1.0180	4.8361	21.0
09:01:10:00	43.6	26.6	13.4	36.0	17.0	91	504			
								1.3165	3.5396	37.2
09:01:10:30	49.3	28.0	13.5	39.1	19.3	100	504			
								1.6180	5.8640	27.6
09:01:11:00	55.5	29.7	13.6	42.9	22.2	107	504			
								1.8428	6.2032	29.7
09:01:11:30	60.3	31.2	13.9	44.2	25.4	116	504			
								1.9697	6.4143	30.7
09:01:12:00	62.7	32.0	14.1	46.1	28.9	116	504			
								2.0987	6.5296	32.1
09:01:12:30	64.7	32.9	15.0	46.5	32.6	122	504			
								1.9093	6.5197	29.3
09:01:13:00	64.1	34.8	18.9	47.6	36.0	123	504			
								1.6008	6.4056	25.0
09:01:13:30	64.3	38.7	25.4	50.3	38.8	125	504			
								1.3252	6.1410	21.6
09:01:14:00	64.4	41.8	30.8	52.0	41.1	129	504			
								1.0612	5.7384	18.5
09:01:14:30	63.7	44.3	35.0	53.8	43.0	125	504			
								0.8596	5.2553	16.4
09:01:15:00	61.6	45.6	38.0	53.8	44.5	122	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.9 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					12.6					
								0.4628	0.7665	60.4
09:02:09:00	29.6	21.7	13.0	27.3	13.4	68	504			
								0.6576	2.3856	27.6
09:02:09:30	35.9	23.6	12.8	31.7	14.5	79	504			
								0.9779	4.8927	20.0
09:02:10:00	42.7	25.5	12.8	34.9	16.2	94	504			
								1.2101	3.5602	34.0
09:02:10:30	49.1	27.2	13.0	38.2	18.4	105	504			
								1.5811	5.8338	27.1
09:02:11:00	54.8	28.4	13.2	41.2	21.2	114	504			
								1.7465	5.9418	29.4
09:02:11:30	58.7	29.9	13.3	43.6	24.2	115	504			
								1.8364	6.4938	28.3
09:02:12:00	61.6	30.9	13.5	45.1	27.5	118	504			
								1.8272	5.8981	31.0
09:02:12:30	60.0	30.6	13.8	44.0	30.7	118	504			
								1.7265	6.6584	25.9
09:02:13:00	60.4	32.1	16.0	44.9	33.7	118	504			
								1.5550	5.8389	26.6
09:02:13:30	58.1	34.5	21.9	45.7	36.5	120	504			
								1.1108	5.6545	19.6
09:02:14:00	59.2	37.9	27.5	47.5	38.4	129	504			
								0.8907	5.0119	17.8
09:02:14:30	56.3	39.8	31.7	48.3	40.0	120	504			
								0.7401	5.3703	13.8
09:02:15:00	57.3	42.1	35.0	50.1	41.3	122	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.9 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-w (%)
					12.3					
								0.4278	0.7629	56.1
09:03:09:00	30.2	21.6	12.3	28.3	13.0	65	504			
								0.7306	2.5724	28.4
09:03:09:30	36.8	23.5	12.4	31.4	14.3	85	504			
								1.0923	4.9158	22.2
09:03:10:00	44.5	25.6	12.6	35.5	16.2	100	504			
								1.3720	3.5435	38.7
09:03:10:30	51.2	27.3	12.8	39.0	18.7	110	504			
								1.7237	5.8744	29.3
09:03:11:00	57.7	29.2	13.1	42.2	21.7	119	504			
								1.9711	6.2092	31.7
09:03:11:30	62.2	30.5	13.3	44.7	25.2	122	504			
								2.0497	6.4504	31.8
09:03:12:00	64.8	31.4	13.4	46.3	28.8	123	504			
								2.2024	6.6122	33.3
09:03:12:30	66.5	32.2	14.2	47.0	32.7	126	504			
								2.0589	6.6232	31.1
09:03:13:00	66.1	34.5	18.6	48.2	36.3	129	504			
								1.6714	6.2245	26.9
09:03:13:30	64.6	38.3	26.0	49.9	39.2	133	504			
								1.0723	3.4691	30.9
09:03:14:00	55.1	39.1	30.8	47.3	41.1	118	504			
								0.7752	5.0319	15.4
09:03:14:30	60.5	42.8	34.6	51.5	42.5	126	504			
								0.7495	4.5067	16.6
09:03:15:00	59.3	44.6	37.6	52.2	43.8	122	504			

TABLE A2 (cont.): 1982 Test Data

Tank Elevation= 0.9 m

Date-time	Ta-i (C)	Ta-o (C)	Tw-i (C)	Tw-o (C)	Ttank (C)	Mwat (kg/hr)	Mair (kg/hr)	Ener-tank (kWh)	Ins (kWh)	Eff-W (%)
					13.5					
								0.5001	1.1510	43.5
09:10:09:00	31.1	22.5	13.1	28.7	14.4	66	504			
								0.7150	3.3063	21.6
09:10:09:30	36.5	24.2	13.2	31.6	15.6	81	504			
								1.0576	4.5930	23.0
09:10:10:00	42.6	25.8	13.4	34.9	17.5	94	504			
								1.2436	3.6920	33.7
09:10:10:30	48.2	27.4	13.4	38.2	19.7	102	504			
								1.5344	5.7601	26.6
09:10:11:00	53.7	28.7	13.6	40.9	22.4	110	504			
								1.7499	6.1422	28.5
09:10:11:30	58.3	30.2	13.8	42.8	25.5	117	504			
								1.8808	6.4272	29.3
09:10:12:00	60.1	31.0	14.1	43.6	28.8	119	504			
								1.8536	6.5220	28.4
09:10:12:30	61.4	31.7	15.0	44.2	32.0	123	504			
								1.8132	6.4581	28.1
09:10:13:00	61.7	34.0	19.4	46.2	35.2	125	504			
								1.4720	6.2707	23.5
09:10:13:30	61.8	37.7	25.7	48.6	37.8	127	504			
								1.2268	6.0593	20.2
09:10:14:00	61.8	40.5	30.4	49.9	40.0	132	504			
								1.0065	5.6500	17.8
09:10:14:30	61.1	42.7	33.9	51.5	41.8	128	504			
								0.8091	5.1564	15.7
09:10:15:00	58.9	44.0	36.7	51.8	43.2	119	504			

1. Tank Elevation= vertical distance between tank outlet and collector outlet, m
2. Date-Time= month:day:hour(local solar time):minutes
3. Ta-i= temperature of air intering the heat exchanger, C
4. Ta-o= temperature of air leaving the heat exchanger, C
5. Tw-i= temperature of water entering the heat exchanger, C
6. Tw-o= temperature of water leaving the heat exchanger, C
7. Ttank= average temperature of the water storage, C
8. Mwat= average water flow rate during 30 minute interval, kg/hr
9. Mair= air flow rate in the collector, kg/hr
10. Ener-tank= energy added to water storage during 30 minute interval, kWh
11. Ins= average insolation from measurements taken every minute over the 30 minute interval, kWh
12. Eff-W= Ener-tank/Ins for the 30 minute interval, %